Tatiara PWA numerical groundwater flow model and projected scenarios: Volume 1

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Foreword

The Department for Environment and Water (DEW) is responsible for the management of the State's natural resources, ranging from policy leadership to on-ground delivery in consultation with government, industry and communities.

High-quality science and effective monitoring provides the foundation for the successful management of our environment and natural resources. This is achieved through undertaking appropriate research, investigations, assessments, monitoring and evaluation.

DEW's strong partnerships with educational and research institutions, industries, government agencies, Natural Resources Management Boards and the community ensures that there is continual capacity building across the sector, and that the best skills and expertise are used to inform decision making.

John Schutz
CHIEF EXECUTIVE
DEPARTMENT FOR ENVIRONMENT AND WATER

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At the time of writing the Department for Environment and Water (DEW) was the Department for Environment, Water and Natural Resources (DEWNR). It should be acknowledged that all DEWNR branding in this report is considered equivalent to DEW.

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Summary

The Tatiara Prescribed Wells Area (PWA) groundwater model has been developed to investigate the potential influence of varying groundwater extraction and climate induced stresses on groundwater resources in the future. The model is to be used as a tool to enable policy settings to be explored during the revision of the Tatiara PWA Water Allocation Plan. To do this, the model must be able to simulate the regional levels and trends of the groundwater system over the historical period (1985–2015) in response to the observed changes in rainfall and estimates of groundwater extraction. This has been done using an iterative calibration approach that applies automated parameter estimation software in combination with manual adjustments based on hydrogeological knowledge. A family of three groundwater models were calibrated using a range of different scaling factors applied to historical groundwater extraction estimates, in order to capture some of the uncertainty introduced by unmetered extraction. Overall, the model shows good agreement between the observed and simulated groundwater levels in terms of level and trends. Declining trends are slightly under-predicted in parts of the coastal plain over the last five years of the calibration period and over-predicted in the Mallee highland over the last ten years. Groundwater mass balances of the Tatiara PWA are considered to be improvements on previous assessments (e.g. Stadter and Love, 1987; Cobb and Brown, 2000) which generally fall within the variation captured by the models. An assessment of the confidence rating for the model performance has been done for each of the 312 observation wells used in calibration. A high to medium confidence can be placed on the simulated water levels of 71% of observation wells while 15% of observation wells were simulated with a low confidence and 14% could not be assessed due to a lack of time-series data. It is recommended that future groundwater projections be used in a relative sense in areas of low or not-assessed confidence.

Four variations of groundwater extraction were projected into the future and combined with two climate scenarios – theintermediate emissions scenario (RCP4.5) and the high emissions scenario (RCP8.5) (each with three climate datasets). Diffuse recharge decreases on average over the next 30 years for both climate scenarios while point recharge (through runaway holes) is more variable and dependent on large rainfall events. Average diffuse recharge ranges from 62–85 GL/y for the high carbon emissions scenario which is greater than the 2006–15 average, while average recharge in the intermediate carbon emissions scenario ranges from 78–112 GL/y and is more like the average recharge from 1996–2005. The average storage losses continue in each scenario but are smaller in magnitude between scenarios when extraction is lower. Average inflow fluxes show only small increases into the future suggesting that the larger fluctuations of other mass balance components within the Tatiara PWA do not cause large or immediate responses from the eastern part of the groundwater system (i.e. SA–Victoria Border) within the model projection period (ending in 2045). Potential impacts beyond this time period are likely to be seen later given the continued losses from storage and the gradual decline in average recharge projected over the next 30 years. Outflow towards the west decreases over time for only the full allocation scenario (131 GL/y), while the scenarios with lower extraction rates show relatively constant or increasing outflow fluxes. This suggests that the coastal plain groundwater system becomes somewhat stable for the periodic (89–93 GL/y), current (84 GL/y) and lower (63 (GL/y) extraction scenarios while the overall continued loss of storage occurs in the Mallee highland adjacent to the coastal plain due to historical groundwater level declines.

The outputs of the model are tailored towards informing possible resource condition limits (RCLs – representing an agreed unacceptable condition of the resource) developed by Cranswick and Barnett (2017) for the coastal plain and Mallee highland hydrogeological zones. The RCLs are not exceeded on the Mallee highlands or the three lowest extraction scenarios on the coastal plain (ranging from 63–97 GL/y). However the full allocation scenario (131 GL/y) results in RCL exceedances for the coastal plain and larger groundwater level declines in the Mallee highlands. These exceedances would have major negative implications for the condition of groundwater resources on the coastal plain which should be avoided. The RCL for the Mallee highlands is not exceeded in any scenario despite the continued declines in projected groundwater levels. It is possible for greater rates of extraction to occur in the Mallee highlands without exceeding the proposed hydraulic gradient RCL. Additional scenarios testing the influence of greater extraction from the Mallee highlands areas may provide a useful alternative to the historically dominant extractions from the coastal plain groundwater resources. The possible RCLs used in this report require further refinement prior to being implemented within the Water Allocation Plan, primarily through more robust and

accurate definition of the aquifer performance RCL on the coastal plain (i.e. the extent of saturated Padthaway Formation from which high groundwater yields are currently available for flood irrigation).

1 Introduction

1.1 Background

Previous groundwater resource management investigations commissioned by the Government of South Australia (e.g. Harrington and Currie, 2008) have recommended developing management practices to be better able to respond and adapt to the changing condition of groundwater resources in the South East NRM region. The primary changes to the condition of the groundwater resources are: 1) declines in water levels (i.e. reducing aquifer storage and availability) due to a combination of low rainfall years and ongoing extraction for irrigation, and 2) increases in groundwater salinity due to irrigation recycling and the impacts of clearing native vegetation. Adaptive management approaches should include both an initial assessment of the sustainable yield of the groundwater resources (and / or resource capacity) and an ongoing program of varying allocations depending on the condition of the resource in specific hydrogeologically based management areas. A pilot study was subsequently undertaken (McIntyre and Wood, 2011) focusing on part of the Tatiara Prescribed Wells Area (PWA) and demonstrating that a more adaptive approach is feasible. The need to move to such an approach is also being highlighted by increasing pressures on the groundwater resources in the PWA and elsewhere in the South East region. As a result, work is required to extend the pilot study to incorporate the full Tatiara PWA and 10 km into surrounding areas in order to provide technical support during the development of updated management settings as part of revision of the Tatiara Water Allocation Plan (WAP).

Natural Resources South East has engaged the Science Branch of the Department of Environment, Water and Natural Resources (DEWNR) to perform a series of investigations in the Upper South East region. These are to be delivered in three internally and externally reviewed technical reports that are focused on a range of important aspects of groundwater resource management:

- **Cranswick and Barnett (2017)** – revises the hydrogeological conceptual models for the Upper South East PWAs in order to better describe resource condition indicators and develop possible resource condition limits (RCLs). These RCLs are to be tested in the Tatiara PWA groundwater model to allow stakeholders to establish a view on what unacceptable conditions might be for the purposes of the WAP.
- **Morgan et al. (2017)** – develops a recharge model for the Upper South East region using LEACHM which integrates the influences of unique combinations of climate, landuse, soil type to derive estimates of gross vertical recharge.
- **Li and Cranswick (2017), this report** – develops an updated and extended numerical groundwater flow model for the Tatiara PWA to enable resource management decisions and policy settings to be determined in support of a revised Tatiara PWA Water Allocation Plan (WAP).

1.2 Objectives and scope of work

The specific objectives of this numerical modelling investigation are summarized below:

- Construct a fit-for-purpose model that simulates the regional behavior of the groundwater system in the Tatiara PWA as it responds to changes in recharge and groundwater extraction
- Produce outputs that are tailored towards informing potential management decisions and policy settings for future revisions of the Tatiara PWA WAP
- Ensure that the model results directly relate to the possible RCLs of Cranswick and Barnett (2017)
- Develop and run a series of future scenario projections whose implications are presented within the context of RCLs.

2 Hydrogeology and groundwater resources of the Tatiara PWA

2.1 Location and physical setting

The Tatiara PWA is located in the Upper South East region of South Australia (Figure 2.2). The PWA is approximately 3562 km^2 and is divided into two relatively distinct regions – low-lying coastal plain and more elevated Mallee highlands which are separated by a series of dune ridges. The coastal plain is located to the west while the Mallee highlands are found in the east towards the South Australia–Victoria Border. Mean annual rainfall generally decreases from the south-west to the north-east with long-term averages in Keith and Bordertown of 459 and 477 mm/y respectively. Mean annual evapotranspiration (FAO56) is approximately 1200 mm/y and mean annual temperature is about 15 °C, based on average of the current weather stations within the study area. The majority of the PWA has sandy clay or clay loam soils while in the south-eastern corner clay and clay loam soils are found. The lower permeability of these soils are likely to facilitate the generation of runoff that feeds the only two noteworthy ephemeral creeks in the PWA. These are the Tatiara and Nalang Creeks whose flows generally terminate in the vicinity of Poocher and Mundulla (Moot Yang Gunya) Swamps respectively.

2.2 Hydrogeology and conceptual models

The hydrogeology of the Tatiara PWA has been described by Stadter and Love (1987) following earlier work in the south-west of the PWA by Williams (1979) and Stadter (1984) and also later by Cobb and Brown (2000). The Murray and Otway geological basins in which the PWA is situated, are separated by the underlying basement high called the Padthaway Ridge. The location of this boundary is poorly described, which occasionally results in inconsistent naming of the equivalent Murray Group limestone (MGL) and Gambier limestone units for example. Above the basement is a series of thin sandy sub-aquifers that are separated by thick clay sequences, which confine them, in addition to the overlying Ettrick Formation clay. There is limited or no extraction from these confined aquifer systems and few observation wells to support any modelling of their behavior. Hence the focus of this model is the unconfined aquifer which contains vast and widely utilised groundwater resources. Hydrogeological zones 1, 2 and 3 described by Harrington and Currie (2008), generally correspond with the coastal plain and the Mallee highlands (see below description and Cranswick and Barnett, 2017).

Surface geology within the coastal plain consists primarily of the Bridgewater and Padthaway Formations while the Mallee highlands are covered by Molineaux (thin) and Loxton-Parilla sands (Figure 2.3). Regional groundwater flows generally from the east to the west and/or north-west (Figure 2.3). The hydraulic gradient towards the west is relatively flat on the coastal plain and Mallee highlands, while a highland transition is defined by the steep hydraulic gradient (see Cranswick and Barnett, 2017 for more detailed descriptions).

2.2.1 Coastal plain

The coastal plain is underlain by three Quaternary limestone units: the Padthaway, Bridgewater and Coomandook Formations. These formations can be grouped as the Quaternary limestone aquifer because there is generally a high degree of hydraulic connectivity between them (Figure 2.1).

The **Padthaway Formation** is a well-cemented, fine grained limestone with some interbeds of silts and marls but importantly also has extensive secondary porosity in the form of dissolution features that are often well connected. Where these features are intersected by irrigation wells, very large yields up to 300 L/s are possible (Stadter and Love, 1987). If these features are not intersected, the well yields are much lower as inferred by an assessment of airlift yield data (Cranswick and Barnett, 2017). The Padthaway Formation has a total thickness of up to 20 m but the saturated thickness was historically between 10 and 15 m. As this formation was deposited in a lacustrine environment, some parts of the aquifer contain the basal Keppoch Clay Member, which is a green-brown mottled clay that may locally confine parts of the underlying formations.

The **Bridgewater Formation** generally consists of variably cemented fine – coarse grained calcareous aeolian sands with occasional dissolution features. This formation is typically a barrier bar – coastal dune deposit which generally forms elevated dunes. Yields from the Bridgewater Formation are usually lower than from the Padthaway Formation but the aquifer can have a greater saturated thickness towards the eastern margin of the coastal plain.

The **Coomandook Formation** is a sandy and marly limestone comprised of fossiliferous sands, silts and glauconite. This formation is generally not considered to be a high yielding aquifer but in some areas may behave similarly to the adjacent or underlying Murray Group limestone aquifer.

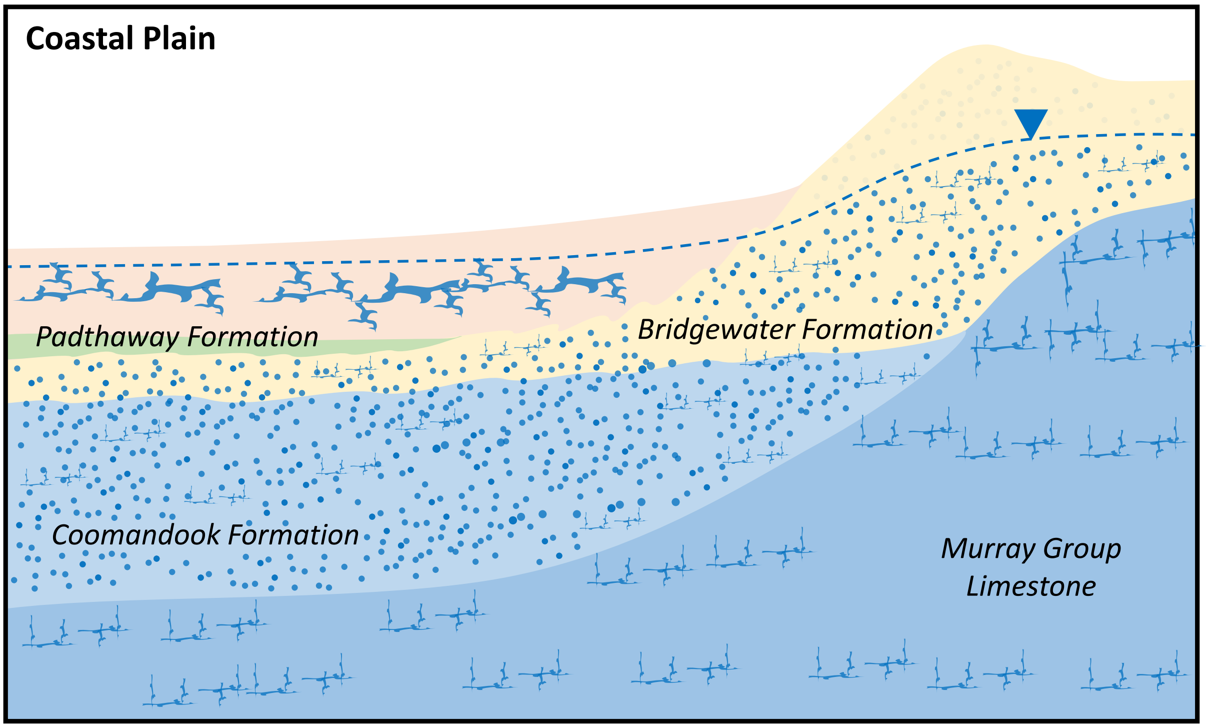

Figure 2.1. Hydrogeological framework of the Quaternary limestone aquifer in the coastal plain (where the dotted blue line represents the watertable surface)

Rainfall is a major source of recharge to the Quaternary limestone aquifer which also receives a considerable volume of groundwater throughflow from the highland areas to the east. The majority of hydrographs in this area show seasonal variations of 1–5 m in response to both diffuse recharge (rainfall and irrigation) and groundwater extractions depending on the distance from extraction wells. Groundwater level responses to point recharge occurring in Poocher Swamp can be up to 10 m and presumably similarly large groundwater responses occur near other runaway holes. Groundwater level trends were relatively stable until the mid-1990s when declines began and continued until present due to continued groundwater extraction in combination with changes in rainfall recharge. In some areas the declines have lessened or stabilised to some degree but remain 3–4 m below the groundwater levels of the mid-1990s. The breakthrough of higher salinity recharge (after clearance of native vegetation) that was previously stored in the unsaturated zone has been largely realised (Wohling, 2007). The vertical variability in salinity that was historically observed, has now been mixed due to extraction and irrigation recycling, which is the dominant process responsible for the recent increasing trends in groundwater salinity (Cobb et al., 2000; Brown et al., 2006; Wohling, 2007).

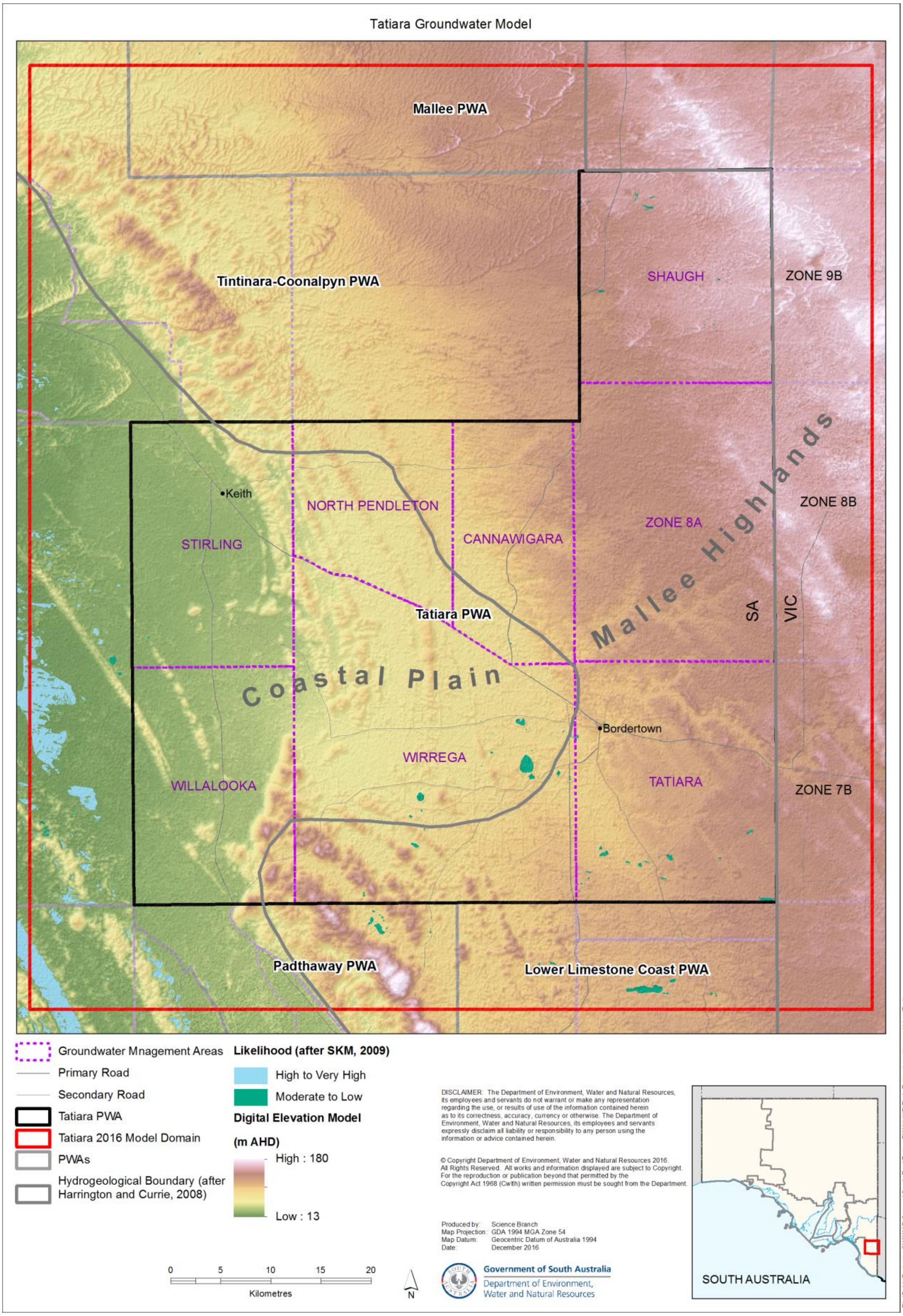

Figure 2.2. Location of Tatiara PWA groundwater model domain and hydrogeological zones

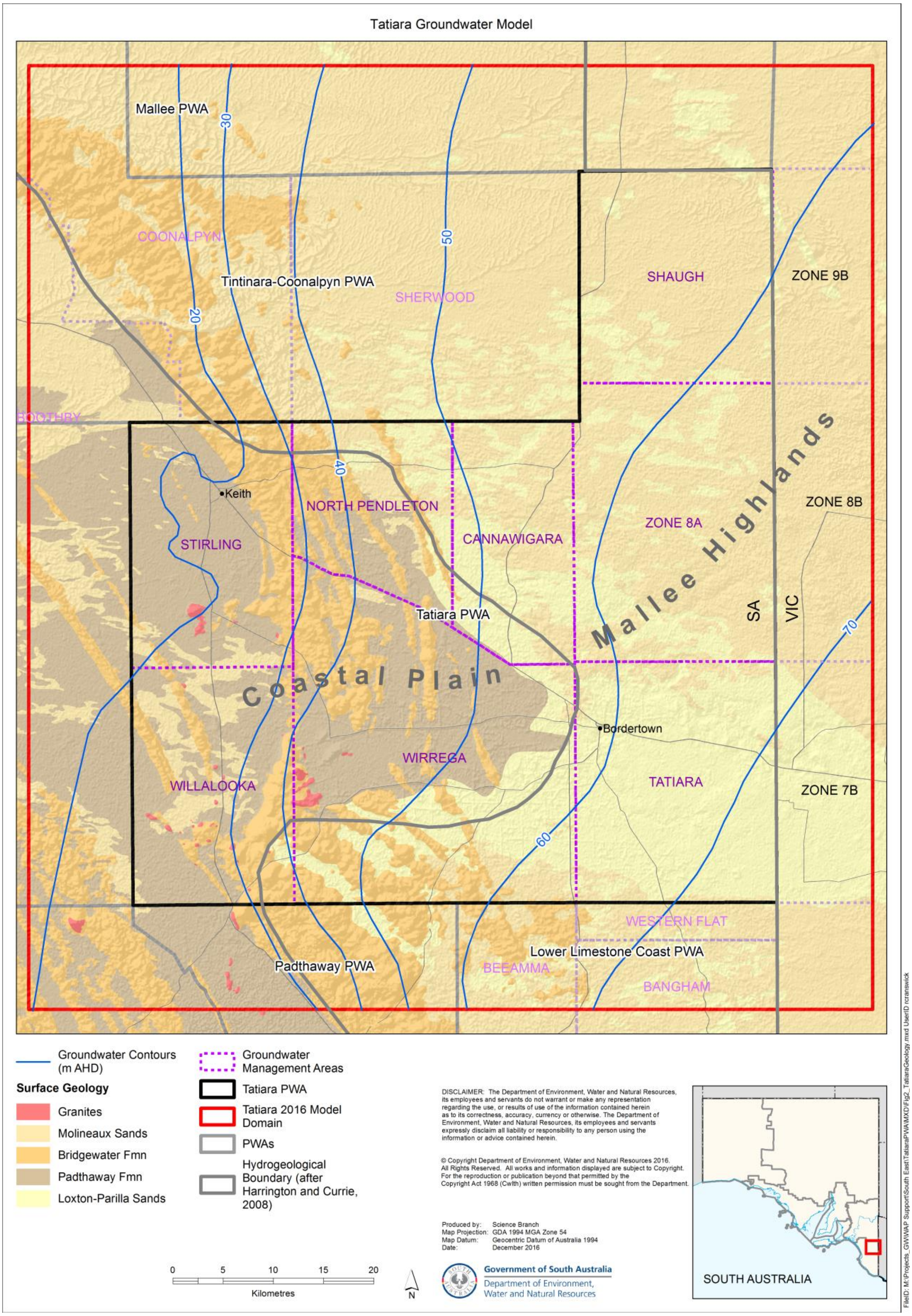

Figure 2.3. Surface geology and groundwater level contours (2010–15 winter average) of the model domain

A sustainability issue is the potential dewatering of the higher yielding parts of the aquifer (particularly the Padthaway Formation) by declines in groundwater levels caused by continued extraction and reduced recharge in a drying climate (Crosbie et al., 2013). This will decease well yields and may make flood irrigation unviable. Well deepening may be necessary to ensure continued groundwater supplies. The behaviour of the aquifers is not well understood once groundwater levels fall below the historical minimum level, but if the permeability and porosity decreases with depth, it may be possible for the rate of decline and seasonal drawdowns to increase even if the extraction rate does not increase above current levels. Similarly, continued increasing trends in groundwater salinity are likely to reach absolute values where the use of the resource will become unviable for current uses (for further discussion see Cranswick and Barnett, 2017).

Reported transmissivity values from aquifer tests within the Quaternary limestone aquifer in the Upper South East region range from 1130–13 000 m^2d^{-1} (Mustafa and Lawson, 2002; Stadter and Love, 1987). As wells are often screened or completed as open hole across multiple formations, it is not possible to confidently associate a range of transmissivity values with each formation.

2.2.2 Transition zone

The extent of transition zone is based on the area where there is a steep hydraulic gradient between the Mallee highlands and the coastal plain from approximately 40–25 m AHD in the north and 45–30 m AHD in the south. This transition zone is loosely similar to those proposed by Stadter and Love (1989) and Wood (2011) but defined strictly by the area with a steep hydraulic gradient (i.e. fall of 15 m over distances of 3–10 km). The transition zone generally contains unconfined aquifers within the Bridgewater Formation and underlying MGL but can also contain other Quaternary limestone units above the MGL.

Reported transmissivity values from aquifer tests within these aquifers in the USE range from 190–6160 m^2d^{-1} (Mustafa and Lawson, 2002; Stadter and Love, 1987). These values are representative of a range of depth intervals within each or both aquifers.

2.2.3 Mallee highlands

The MGL is the most extensive aquifer in the region and is overlain in the Mallee highlands by the Molineaux (thin) and Loxton-Parilla Sands and underlain by the Ettrick Marl (Figure 2.4). The MGL is a poorly to well-cemented fossiliferous limestone with interbeds of sand and marl. There are dissolution features that have developed at multiple depths within the aquifer due to rainfall recharge and watertable fluctuations during the Quaternary Period. Therefore, it is likely that the relatively high yields experienced at shallower depths within the aquifer may also be found at greater depths. It is possible that the hydraulic conductivity of the MGL is be relatively constant with depth since the median airlift yield increases as depth of wells below the watertable increases (see discussion in Cranswick and Barnett, 2017).

The Loxton-Parilla Sands are comprised of aeolian and fluvio-lacustrine deposits but are generally unsaturated due to the deep watertables in the Mallee region. There are some sandy clays which are believed to confine the MGL aquifer in the far north-east corner of the Tatiara PWA (Bradley et al., 1995) and the Bookpurnong Formation further north into the Murray Basin. The presence of clays is thought to prevent significant rates of modern recharge from occurring in areas where they exist extensively. The MGL primarily receives rainfall recharge and in some areas considerable point recharge through runaway holes at the terminus of surface drainage features (e.g. like Poocher and Mundulla Swamps on the coastal plain but on a smaller scale). Considerable throughflow also enters the aquifer from the east which originates as rainfall recharge in Victoria. Groundwater hydrographs are very stable in the east due to the dampening of seasonal recharge inputs caused by thick unsaturated zones (i.e. up to 60 m). In the western parts of the aquifer towards the coastal plain, seasonal variation in water levels are seen in response to rainfall recharge typically of less than 1 m while local drawdown due to groundwater extraction can be in the order of meters. Groundwater level responses to point recharge through runaway holes are presumably similar to those observed near Poocher Swamp. Some hydrographs near the boundary between the Mallee highlands and the coastal plain, show declining trends of 1–3 m since the mid-1990s and subtle changes in salinity (see Cranswick and Barnett, 2017). The breakthrough of initially higher salinity recharge (after clearance of native vegetation) has not yet been observed where the unsaturated zone is thick, particularly towards the east (Wohling, 2007).

A continued decline in groundwater levels due to ongoing extraction and a drying climate would reduce the volume of groundwater that is available from the aquifer (i.e. as it is dewatered). Given the considerable saturated thickness of the MGL aquifer (i.e. up to 90 m in the east) this may not appear to be of concern in the short term. However, long term groundwater declines would require shallow wells to be deepened to ensure continued access to groundwater supplies. Such a decline could also reduce the regional hydraulic gradient towards the coastal plain aquifers resulting in decreased throughflow, which is currently critical for the replenishment of those resources. Additionally, the behavior of the aquifer is not well understood once groundwater levels go below historical minimum levels. Reported transmissivity values from aquifer tests within the MGL aquifer in the Upper South East range from 460–8000 m^2d^{-1} (Lawrence, 1975; Mustafa and Lawson, 2002; Stadter, 1989; Stewart, 1990).

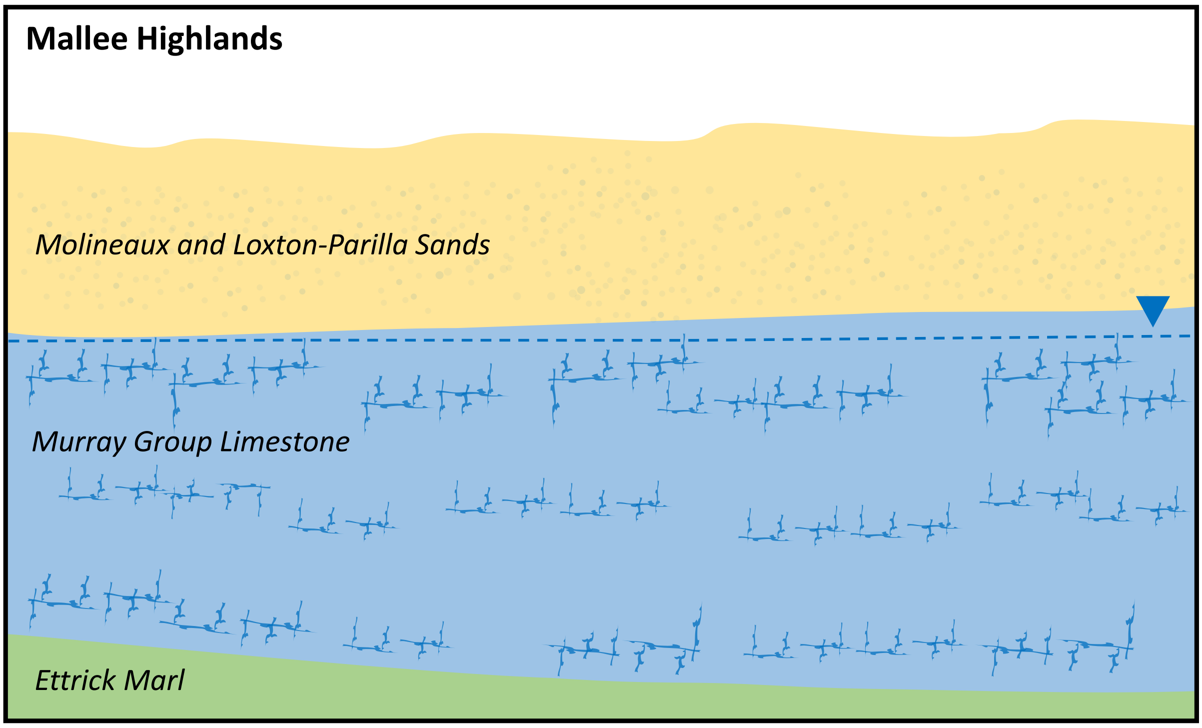

Figure 2.4. Hydrogeological framework of the Mallee highlands

2.2.4 Point source recharge

Point source recharge through runaway holes (including a minor contribution from drainage bores) has been loosely estimated to be approximately 10% of total recharge in the eastern portion of the South East (Leaney and Herczeg, 1995). There is considerable difficulty in constraining this type of recharge since runaway holes generally lack flow gauges on their drainage sources and there are very few creeks of significance in the Tatiara PWA in particular. Exceptions to this include Tatiara and Nalang Creeks, which flow into Poocher and Mundulla Swamps respectively. These creeks have historical flow gauging data which have been used in an assessment of the relationship between rainfall and flow for these creeks by Gibbs (2010). The author developed a statistical relationship between winter rainfall and gauged flow in both creeks.

The best correlation between rainfall and measured flow was found using May–August (inclusive) rainfall using the Bordertown rainfall station (025505) according to the relationship below:

$Q = ((Rain_{May-Aug} - p_1) - p_2 * Tanh((Rain_{May-Aug} - p_1)/p_2)) * A$

where Q = creek flow (ML/y), $Rain_{May-Aug}$, p_1 = parameter 1, p_2 = parameter 2 and A = catchment area (km^2)

Values for this relationship for each creek are shown in Table 2.1 while the observed and predicted creek flow are plotted against May–August (inclusive) rainfall in Figure 2.5. The predicted flow rates have been used directly to approximate point recharge based on the Bordertown rainfall occurring during the Tatiara model calibration period.

Table 2.1. Summary of parameters used for the relationship between winter rainfall and creek flow (Gibbs, 2010)

Creek name	p_1	p_2	A (km^2)	R^2
Tatiara Creek	97.37	457.99	818.6	0.79
Nalang Creek	147.68	273.14	178.6	0.78

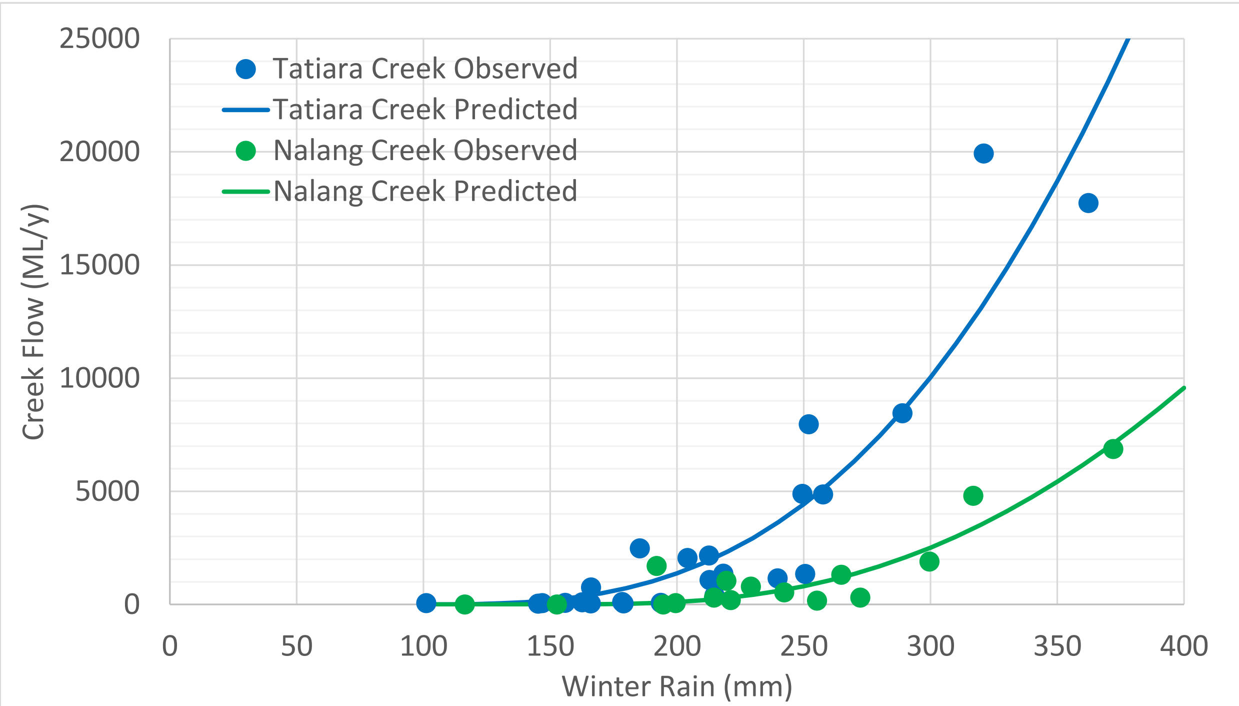

Figure 2.5. Observed and predicted creek flow against winter rainfall (May–August)

2.3 Groundwater monitoring

An extensive groundwater level monitoring network exists in the USE region, particularly for the unconfined aquifers which include some continuous datasets collected from prior to the 1960s to the present time. In more recent decades the quality of the network has been reduced (i.e. in terms of number of observation wells and monitoring frequency) but remains adequate for most management and many research purposes. Groundwater observation wells from the unconfined aquifer with more than 5 data points between 1985 to September 2015 have been used in model calibration. This includes 149 observation wells from within the Tatiara PWA, 158 from surrounding Hundreds (i.e. Laffer and Petherick), Groundwater Management Areas (GMAs) within SA and an additional 5 wells from Victoria in the Border Designated Area.

2.4 Historical development and groundwater extraction

Groundwater development for agriculture in the Tatiara PWA first started in the Hundreds of Stirling, Willalooka and Wirrega in the middle of last century (Williams, 1979). The agricultural areas and total extraction were generally small (i.e. approximately 30 GL as reported by Williams, 1979) until the mid-1970s into the 1980s, when the irrigation of lucerne for seed and pasture increased the volumes of marginal-quality groundwater extracted in the western coastal plain (i.e. > 55 GL as reported by Stadter and Love, 1987). The vast majority of groundwater extraction still occurs in the Hundreds of Stirling and Wirrega followed by Willalooka, North Pendleton and. This intensity in the west is largely due to the irrigation methods used in each area, in combination with aquifer yields, crop and soil type which each influence the distribution of groundwater use in the PWA. Irrigation of potatoes in the east and north-east of the PWA in addition to the irrigation of wine grapes in the south-east, have in recent years increased the volumes of groundwater extracted in the eastern GMAs.

A number of town water supplies have been sourced from groundwater (e.g. Bordertown) for many decades in addition to regional stock and domestic supplies, the latter of which are unmetered.

Total yearly volumes of licensed extraction within the PWA between 2005 and 2015 are reported to range from 58–112 GL, with metered data becoming available since the late 2000s.

2.4.1 Tatiara and adjacent PWA extraction datasets

Metered groundwater extraction data were collated from a range of sources including the DEWNR Licensing group, the WILMA database and internal DEWNR spreadsheets for the relevant PWAs. This data was combined with total volumes for each GMA from Cobb and Brown (2000) whose estimates are based on crop requirements (Figure 2.6). It is necessary to apply a scaling factor to these estimates, particularly on the coastal plain where flood irrigation is common because more groundwater is required to adequately deliver the crop requirement volumes due to losses (i.e. transmission losses due to infiltration and evaporation as well as to allow adequate flushing of soil salinity). Stadter and Love (1987) suggest this scaling factor could range from 1.4 to 2 and this scaling is also supported by discussion in Cobb and Brown (2000). This is an important decision point because the actual groundwater extraction prior to the availability of metered data contains large uncertainty. We have chosen to create three models based on this single assumption using scaling factors of 1.4, 1.6 and 1.8 that have been applied to the groundwater extraction occurring on the coastal plain prior to the start of metered data. Given that extraction volumes on the coastal plain are dominated by flood irrigators where return flows have been estimated to range from 24–71% with an average of 51% (De Barro, 2005) these scaling factors are considered appropriate (i.e. a scaling factors of 1.4, 1.6 and 1.8 equate to return flows of 29, 37 and 44% respectively). Larger scaling factors result in historical estimates that are considered to be unrealistically high and higher than the largest metered extraction values. To account for irrigation inefficiency on the Mallee highlands, scaling factors of 1, 1.15 and 1.3 have been applied. These three variations in estimated groundwater extraction are shown in Figure 2.6.

For the remainder of the report the models with scaling factors of 1.4, 1.6 and 1.8 applied to the coastal plain historical extraction (and 1, 1.15 and 1.3 applied to the Mallee highlands) are referred to as Model A (green symbols), Model B (orange symbols) and Model C (blue symbols) respectively. Often values from Model B are presented in figures for simplicity while complete summaries are found in appropriate tables.

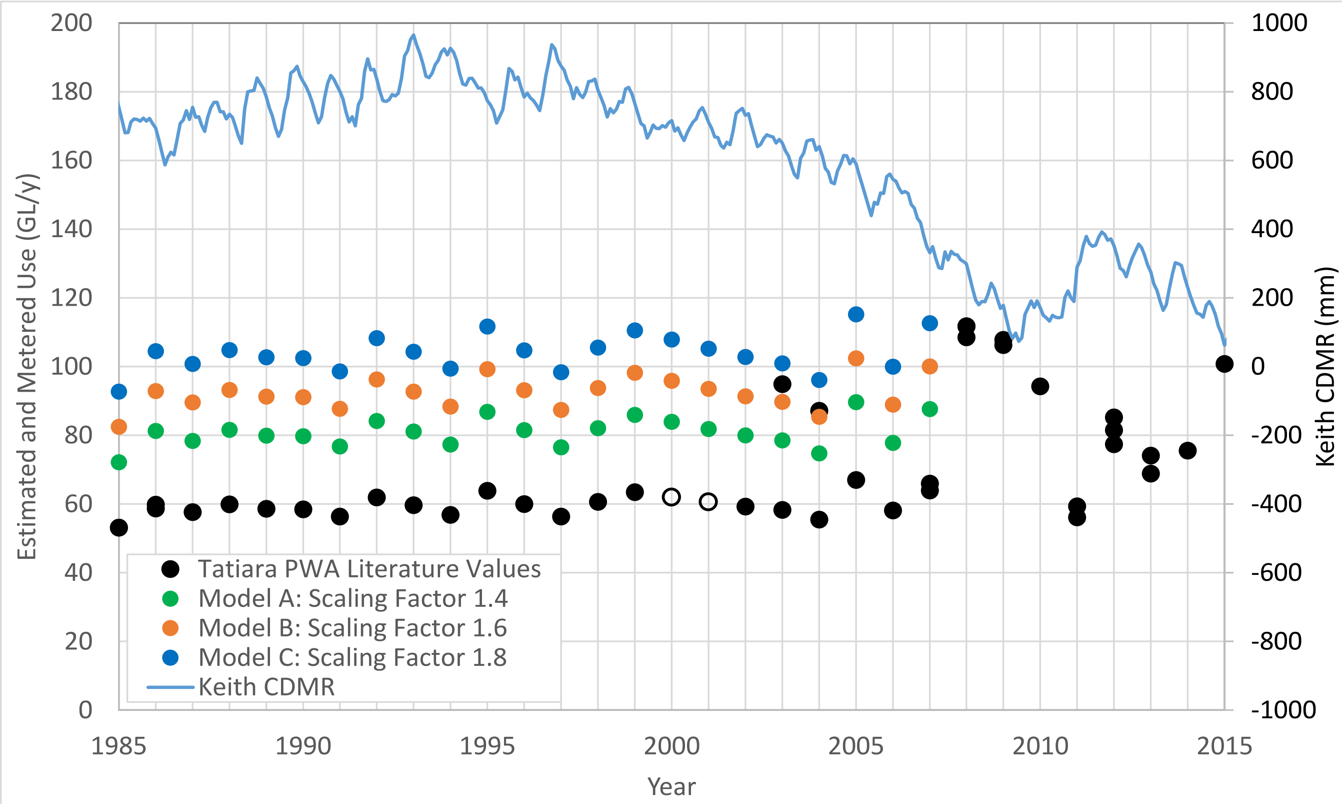

Figure 2.6. Literature estimates and metered groundwater extraction in the Tatiara PWA with a series of scaling factors applied to the historical crop requirement based estimates

Total extraction estimates for water years 1999/2000 and 2000/2001 could not be found and so are approximated by linearly interpolating between estimates from the preceding and following years. A relationship was found between the extraction in the Tatiara PWA and the surrounding PWAs where metered data was available (2009/10 to 2015/16). Relative to the Tatiara PWA extraction, the fraction of Padthaway, Lower Limestone Coast and Tintinara–Coonalpyn PWAs extraction within the model domain were 0.13, 0.03 and 0.26 respectively. The scaled Tatiara PWA historical totals are applied to the totals of surrounding areas using these fractions as a rough approximation where metered data did not exist (i.e. licensed wells within parts of GMAs in the Tintinara–Coonalpyn, Padthaway and Lower Limestone Coast PWAs).

It is noted that the magnitude of groundwater extraction contains significant uncertainty, but this has been accounted for to some degree by creating a small family of models around this assumption (i.e. with Model A, B and C each model having a different scaling factor). There is also uncertainty in the spatial distribution of groundwater extraction which has been accounted for by applying the total extraction values to the average proportions of each metered extraction well that existed in the 2012/13/14/15 years. An example of the spatial distribution of most recent metered and estimated extraction for the 2015/16 is shown in Figure 2.7. The majority of extraction occurs on the coastal plain while there are also considerable volumes extracted in some areas of the Mallee highlands.

The approach described above assumes that crop area based estimates of groundwater use for the historical period represent the best approximation available (primarily government reports). A recent analysis by Harrington and Li (2015) also approximated historical extraction in parts of the Tatiara model domain using a different approach. They assumed that extraction increased from 0 GL/y in 1970 to more recent metered rates (i.e. average from 2009/10 to 2012/13). Their approach removes licensed extraction wells from the dataset in years prior to their drilled or license activation date, which does not account for well replacement or the relatively stable crop areas across the region (i.e. landuse is reported by Cobb and Brown (2000) to have remained relatively steady since the mid-1980s within the Tatiara PWA). Hence the approach taken by Harrington and Li (2015) results in increasing extraction over time (i.e. approximately doubling since 1985 to recent metered volumes within the Tatiara model domain). Because this approach underestimates extraction prior to the metered averaging period (2009/10 to 2012/13), it is considered inappropriate for the Tatiara PWA.

2.4.2 Hundred of Laffer

Groundwater extraction for the flood irrigation of lucerne crops is known to occur in the Hundred of Laffer just to the west of the Stirling GMA (Barnett and MacKenzie, 2007) but outside of the PWA. A rough approximation of this extraction was made by assuming that the landuse area categorized as "Production from Irrigated Agriculture" required irrigation rates of 12 ML/ha which was distributed evenly between the 42 irrigation wells within the model domain. This amounted to a total of approximately 9030 ML/y or 215 ML/y per irrigation well which is comparable to extraction rates in the adjacent Stirling GMA and considered to be a reasonable approximation. This has been applied at a constant rate through the historical period for simplicity. No extraction was assumed for the Hundred of Petherick (outside of the PWA) to the south of Laffer and west of Willalooka GMA.

2.4.3 Victoria

Metered data for extraction wells from Border Designated Area Zones 6B, 7B, 8B and 9B was not provided by the Victorian Government until after the model construction and calibration had been completed. Therefore no attempt has been made to approximate groundwater extraction in these areas of the model. This limitation is accounted for by using a GHB that approximates any regional cumulative impact of groundwater extraction along the eastern boundary of the model by assigning a time-variable groundwater level (see later description).

Data received from Grampians-Wimmera-Mallee Water (December, 2016), shows that there are only three wells that have considerable extraction within the model domain (i.e. one or more years of >100 ML/y between 2011/12 and 2015/16), and only one hydrograph in these zones appears to be influenced by pumping (i.e. a 0.2 m decline over the last five years). However, this hydrograph has the same coordinates as an extraction well, suggesting that this hydrograph is not impacted by any regional scale influence but rather a very local scale one. An average of 698 ML/y has been extracted over this very large area (i.e. 10 km x 94 km) equating to approximately 0.00035 m/y of water level change (assuming S_y = 0.15) and is therefore not considered critical for the model calibration.

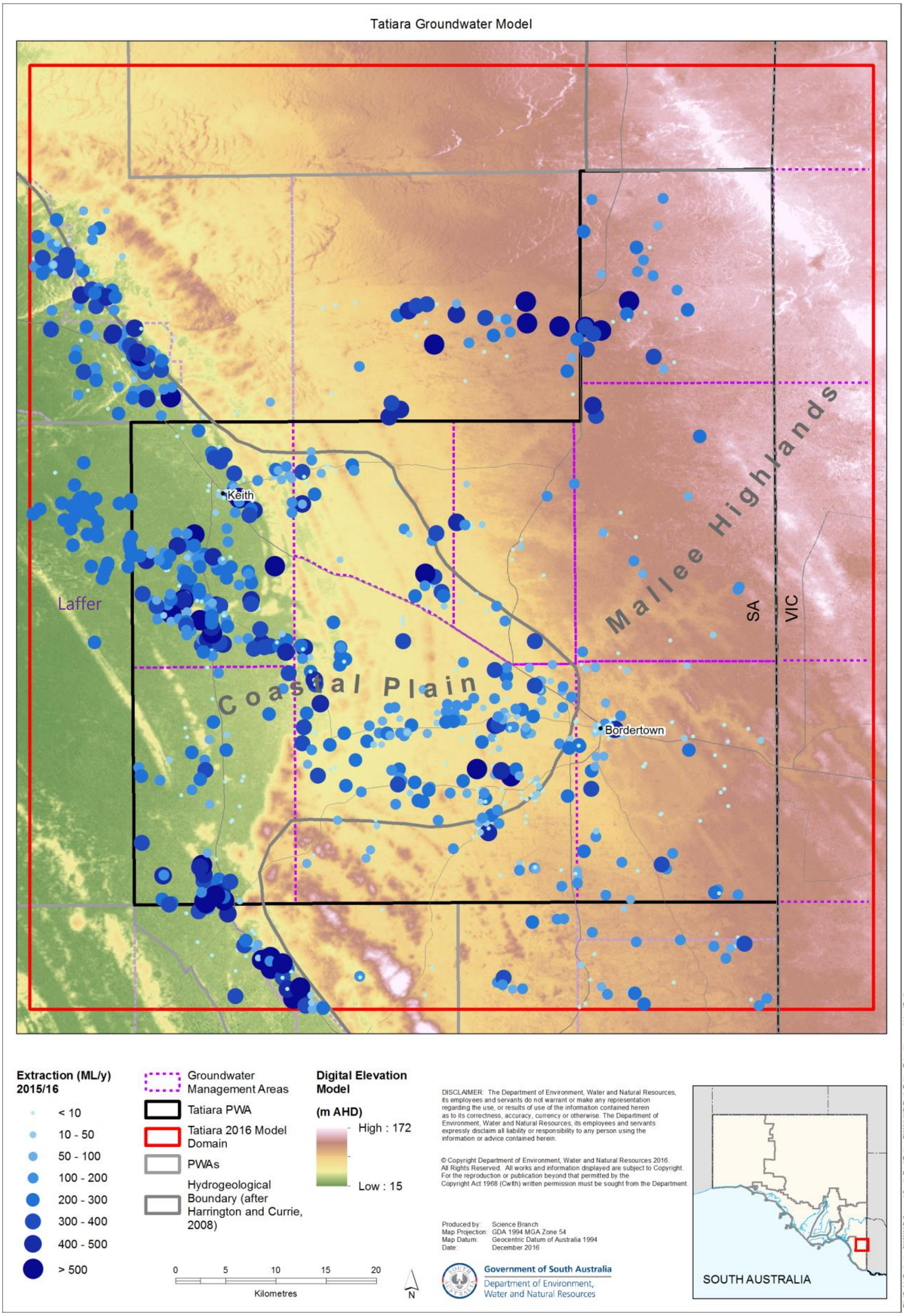

Figure 2.7. Estimated (Hd of Laffer) and metered groundwater extraction within the model domain for 2015/16

2.5 Resource condition indicators and limits

A series of resource condition indicators have been developed by Cranswick and Barnett (2017) for the Upper South East PWAs. As relevant to the Tatiara PWA these include the use of groundwater level and salinity monitoring data for the analysis of aquifer performance, horizontal hydraulic gradients, and both the trends and spatial distribution of groundwater salinity. These RCIs have been developed into possible RCLs, some of which are to be tested in this model report. The RCLs from Cranswick and Barnett (2017) to be incorporated into the model results for the Tatiara PWA are listed below. The purpose of developing RCLs is to allow the objectives of the WAP to be written in reference to specific and measurable indicators of the condition of the resource. This allows agreed unacceptable conditions to be firstly developed by stakeholders and clear management approaches to then be developed in order to avoid such conditions.

Coastal plain

- Aquifer performance – maintain a saturated thickness within the Padthaway Formation of > 3 m at the end of each winter monitoring round.
- Hydraulic gradient – maintain a westward hydraulic gradient of > 0.0001 at all times between paired monitoring wells across the western boundary of each PWA.

Mallee highlands

- Hydraulic gradient – maintain a westward hydraulic gradient of > 0.0004 at all times between paired monitoring wells across the western boundary of the Mallee highlands towards the coastal plain.

A preliminary selection of representative monitoring wells has been conducted and are listed in Table 2.2 below. Four monitoring wells are selected as representative of possible aquifer performance RCL on the coastal plain and three pairs of wells are selected to represent the possible hydraulic gradient RCL in each of the coastal plain and Mallee highlands areas. These RCLs and representative monitoring wells are later presented in Section 6.2.6 with respect to the projections of each future model scenario.

Table 2.2. Preliminary monitoring well selections for possible RCLs in the Tatiara PWA

Possible RCL	Coastal plain	Mallee highlands
Aquifer performance	STR110, STR111, WLL108, WLL105	n/a
Hydraulic gradient	STR110–LAF3, STR114–LAF6, WLL7–PRK37	CAN16–PET15, SEN3–CAN14, TAT108–WRG116

2.6 Summary

The Tatiara groundwater model contains two broad hydrogeological zones containing unconfined aquifers; the coastal plain, and the Mallee highlands. The coastal plain consists of high permeability Quaternary limestone aquifer whose most productive layer is the Padthaway Formation. This layer is underlain the Bridgewater (also found at the surface where the Padthaway Formation is absent) and Coomandook Formations which generally have lower yields. The Mallee highlands contains the Tertiary aged Murray Group limestone aquifer, which has large storage volumes but receives relatively low recharge rates through a thick unsaturated zone.

Most groundwater extraction within the model domain occurs along the coastal plain, which also shows rapid responses to rainfall recharge and irrigation recharge since groundwater is relatively shallow. Seasonal variation in groundwater levels is surprisingly damped in response to these influences while large scale declines in groundwater levels have been observed since the mid-1990s. The declines are thought to be driven by rainfall trends in combination with continuing groundwater extraction. Groundwater salinity is generally higher than elsewhere in the model domain and in some areas show consistent increasing trends that are primarily associated with irrigation recycling. Less extraction occurs in the Mallee highlands despite groundwater having much lower salinity while groundwater levels are generally very stable and show no seasonal variation.

3 Model construction

3.1 Code selection and modelling approach

MODFLOW-NWT (Niswonger et al., 2011) was selected as the numerical code for the Tatiara PWA groundwater model (referred to herein as the Tatiara model). It is a three-dimensional finite difference code developed by the U.S. Geological Survey. It is a variation of MODFLOW-2005 (Harbaugh, 2005) and intended for solving problems involving drying and rewetting nonlinearities of the unconfined groundwater-flow equation. The Padthaway Formation can be very thin in some areas, causing numerical instability to the traditional MODFLOW PCG2 solver. MODFLOW-NWT is found to be able to overcome the instability issue and hence is adopted in the Tatiara model. The model uses the "MODERATE" option for the NWT solver, with a head change criterion of 0.0001 m and a flux change criterion of 500 kL, as recommended by the NWT user manual (Niswonger et al., 2011).

The Tatiara model simulates groundwater flow exclusively within the saturated zone and does not explicitly simulate the unsaturated zone processes. These processes (except groundwater evapotranspiration) are taken into account by adopting the gross groundwater recharge outputs from Morgan et al. (2016), who used the unsaturated zone model LEACHM to calculate vertical water fluxes based on unique combinations of soil, land use, rainfall, potential evapotranspiration (ET), crop type, irrigation and other factors (see Section 3.5.2.1).

The aquifers in the Tatiara PWA contain secondary porosity (i.e. connected fractures and karst features) that are simulated using the Equivalent Porous Medium (EPM) approach. It replaces the primary and secondary porosity and hydraulic conductivity distributions of the aquifer material with a continuous porous medium having so-called equivalent or effective hydraulic properties. Although the EPM approach may poorly reproduce small-scale conditions, in general, it can adequately represent the behaviour of a regional flow system (Anderson and Woessner 1992). The EPM approach is commonly used in other South Australian groundwater models involving dual porosity media, including the Barossa Valley (Li and Cranswick, 2016), the Adelaide Plains model (Bresciani et al., 2015), the South East model (Morgan et al., 2015) and the Cox Creek model (Werner et al., 2014). Simulation of karst features and associated flow patterns require great detail of the local hydrogeological features and long computational times, which is often not practically feasible.

Solute transport is not simulated in the current version of the model. It could be considered in a later phase of model development, although the appropriateness of simulating solute transport in karst aquifers with the EPM approach needs to be considered carefully.

Groundwater Vistas Advanced Version 6 (ESI, 2013) is selected as a pre- and post-processing platform for quick generation of data files for MODFLOW-NWT. It is used to generate model grids, boundary conditions and zones for aquifer hydraulic parameters. The software is also used to set model options, to run the model and to obtain output results.

3.2 Model domain and grid

The study area is the Tatiara Prescribed Wells Area (PWA), which is incorporated within the Tatiara model domain as shown in Figure 2.2. The Tatiara PWA is located in the Upper South East region and consists of the unconfined Groundwater Management Areas (GMAs) of Tatiara, Wirrega, Willalooka, Stirling, North Pendleton, Cannawigara, Shaugh and Zone 8A. The model domain also covers parts of the unconfined GMAs of Sherwood, Coonalpyn, Tintinara, Boothby, Peacock, Marcollat, Beeamma, Bangham, Western Flat, and Management Areas 1, 2A and 4 as well as other surrounding Hundreds and parts of Border Zones 9B, 8B, 7B and 6B in Victoria.The model domain simulates an area of 84 km east–west by 94 km north–south, totalling to 7896 km^2. The bounding GDA 1994 MGA Zone 54 coordinates of the model domain are E422646 N5953652 in the south-west and E506646 N6047652 in the north-east. The grid is orientated north–south and east–west. The rectangular model grid is divided into 470 rows and 420 columns, with a uniform cell size of 200 x 200 m. Applied to two model layers, this results in a total of 394800 cells, of which 394078 are active and 722 are inactive. The inactive cells represent the basement outcrops.

The lateral model domain boundary is extended (in the east, west, north and south directions) 10 km away from the Tatiara PWA to reduce the boundary effect on the model results in the Tatiara PWA. It is acknowledged that there are pumping activities near the model domain boundary, which may be affected by the boundary conditions. However, given the pumping density in the Upper South East, it is impractical to extend the model domain boundary infinitely until there is no nearby pumping. Therefore, setting the model domain boundary 10 km away from the study area is a compromise between reducing the boundary effect whilst keeping the model size reasonable. The fluxes across the boundary conditions are closely monitored during the modelling to ensure they are not constraining the model results within the study area.

3.3 Model layers

The model simulates groundwater flow in the unconfined aquifer using two layers. Each layer is divided into three hydrogeological zones – coastal plain, transition zone and Mallee highlands – in accordance with the hydrogeological framework presented earlier. The layering chosen reflects the regional hydrogeology to the best of current knowledge based on interpreted data and literature. The model layers are described in Table 3.1 and a representative east to west cross-section running approximately through Bordertown is shown in Figure 3.1.

Table 3.1. Summary of sedimentary units represented in each model layer

Model layer	Coastal plain	Transition zone	Mallee highlands
1	Padthaway and Bridgwater Formations	Bridgewater Formation and Murray Group Limestone	Murray Group Limestone
2	Bridgewater and Coomandook Formations	Murray Group Limestone	Murray Group Limestone

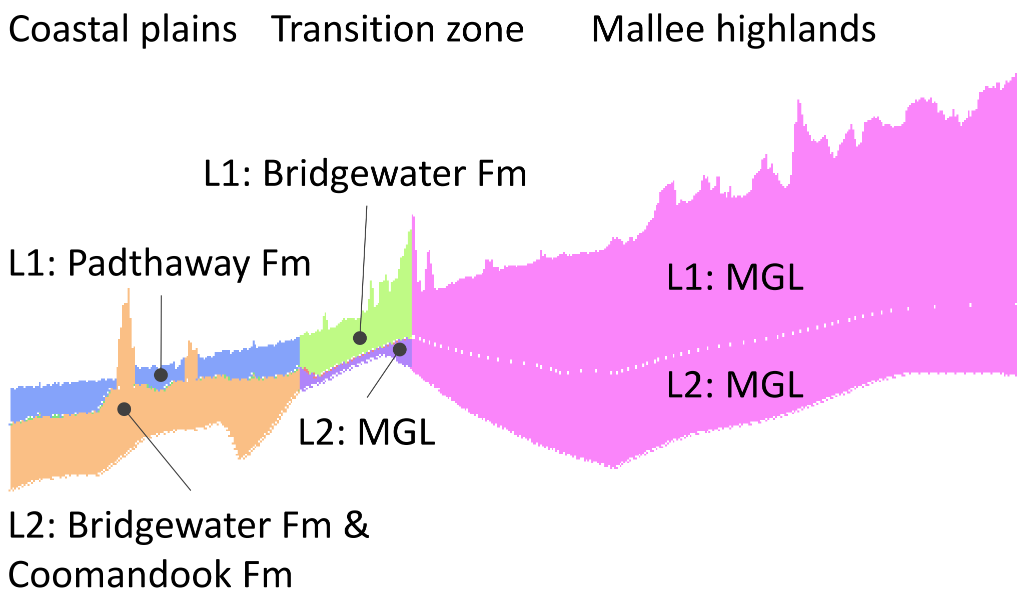

Figure 3.1. Model layers showing an east–west section near Bordertown through row 315, N5984752

3.3.1 Layer 1

The top elevation of layer 1 (Figure 3.2) represents the ground surface. It is sourced from two Digital Elevation Models (DEMs), one for South Australia and one for Victoria. The South East Lidar DEM is used for the South Australian part of the model domain. It is derived from Airborne Laser Scanning acquired over the South East NRM region between 15 Oct 2007 and 22 May 2008, with a resolution of 10 x 10 m. The statewide NASA DEM is used for the Victorian part of the model domain. It is derived from the 1 second Shuttle Radar Topography Mission (SRTM) acquired in February 2000 with a cell size of 30 x 30 m. The boundary between the two DEMs was smoothed to prevent abrupt changes in elevation. The elevation values were averaged for each 200 x 200 m model cell.

The bottom elevation of layer 1 (Figure 3.3) is derived by using multiple approaches and sources depending on the area. In the western part of the model (coastal plain), the extent of the Padthaway Formation is defined by the surface geology data. Where the Padthaway Formation is present, the bottom of layer 1 represents the bottom of the Padthaway Formation, derived from interpolating the existing hydrostratigraphic logs. Where the Padthaway Formation is absent, the Bridgewater Formation and other sandy units are assumed to be present. In this area, these formations are often not clearly distinguished at depth and so they have been grouped together. The bottom of layer 1 is arbitrary set to be the mid-depth between the water table surface (created using the latest observation data) and the top of the Murray Group Limestone surface (after Wright and Risby, 2014).

The hydrogeological unit in the transition zone of model layer 1 is mostly the Bridgewater Formation, where the bottom of layer 1 represents the top of Murray Group Limestone (after Wright and Risby, 2014). However, the hydrostratigraphic data suggest that there is a small area to the north-west of the North Pendleton GMA where the Murray Group limestone is significantly elevated. In this area, the water table is believed to be in this unit and hence model layer 1 represents the Murray Group limestone. As both model layers represent the Murray Group limestone in this area, the bottom of layer 1 was arbitrarily set to be the mid-depth between the water table surface and the bottom of the Murray Group limestone, similar to the approach applied to the Bridgewater and Coomandook Formations on the coastal plain.

In the eastern part of the model (Mallee highlands) the Loxton-Parilla and other sands are considered to be unsaturated and so layer 1 represents the Murray Group limestone. As both model layers represent the same unit, the bottom of layer 1 in the Mallee highlands is arbitrarily set to be the mid-depth between the water table surface and the bottom of the Murray Group limestone, similar to the approach applied to the Bridgewater and Coomandook Formations on the coastal plain.

When the surfaces were merged to form the bottom of layer 1, the bottom of Padthaway Formation on the coastal plain and the top of Murray Group limestone in the transition zone were prioritised and remained unchanged during the merging process. The remaining area was allowed to change to smooth the boundaries between the surfaces. The elevation values were then averaged for each 200 x 200 m model cell.

During the modelling process, a minimum thickness of 3 m (which is 1 m below the ET extinction depth of 2 m) was adopted for layer 1 by adjusting the bottom of layer 1 where necessary. This is to give the model a reasonable saturated thickness after ET is taken into account, which is prominent in the western part of the model domain where the water table is shallow. In addition, the bottom elevation of layer 1 for some model cells was slightly lowered to overcome model convergence and instability issues during calibration.

3.3.2 Layer 2

Layer 2 on the coastal plain contains the Bridgewater and Coomandook Formations (Table 3.1). These two formations have been combined due to insufficient data to support the development of the top surface of the Coomandook Formation. It should be noted that the MGL may also be present in this area but is reported to be thin, absent or undifferentiated and so has not been included explicitly. However since the top of Ettrick Formation was used as the bottom elevation for layer 2 (Figure 3.4, after Wright and Risby, 2014), the thickness of any MGL is represented within this layer. In the transition zone and Mallee highlands, layer 2 represents the Murray Group limestone. The elevation values were averaged for each 200 x 200 m model cell. For consistency, a minimum thickness of 3 m is also adopted for this layer.

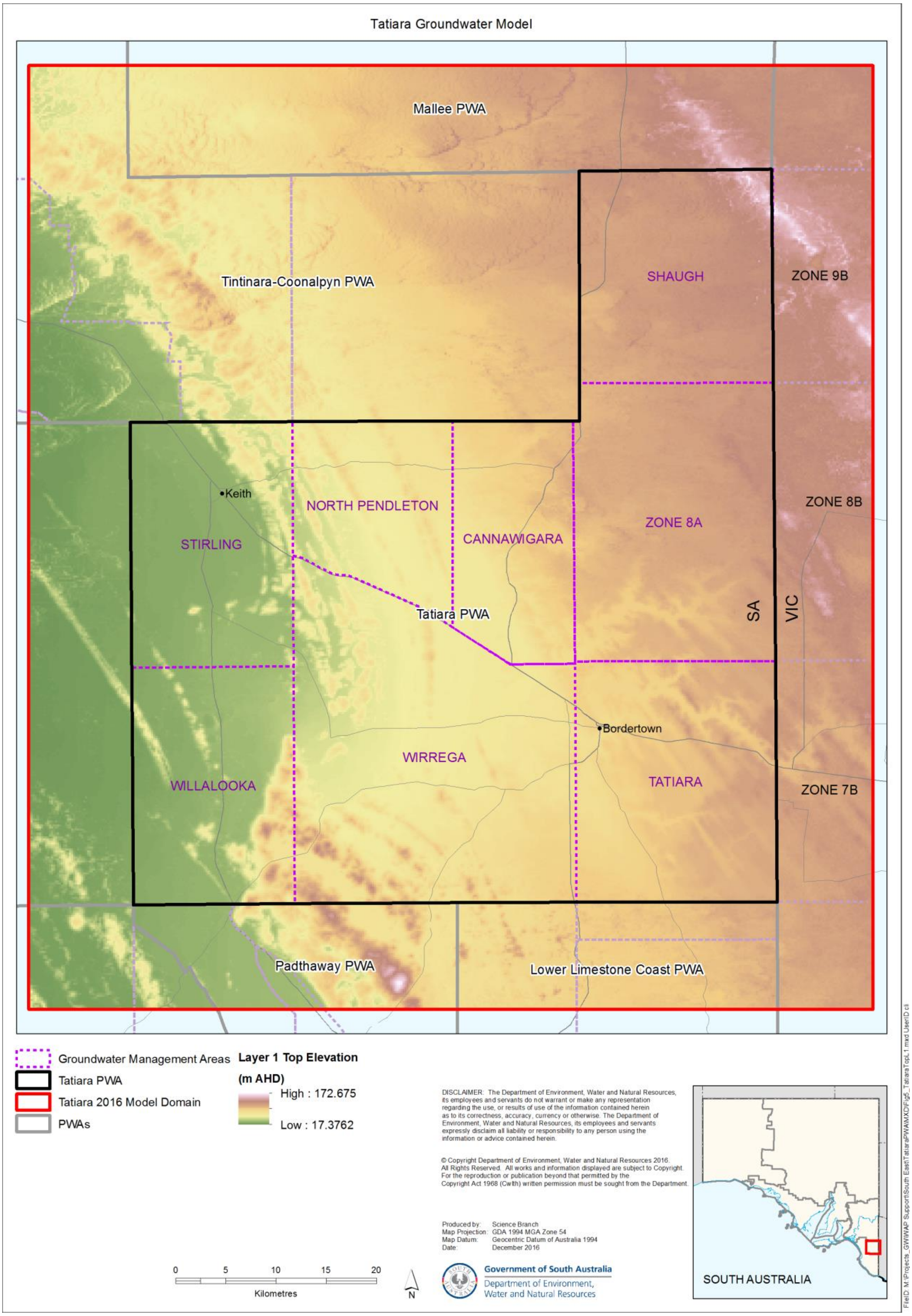

Figure 3.2. Top elevation of model layer 1 (m AHD)

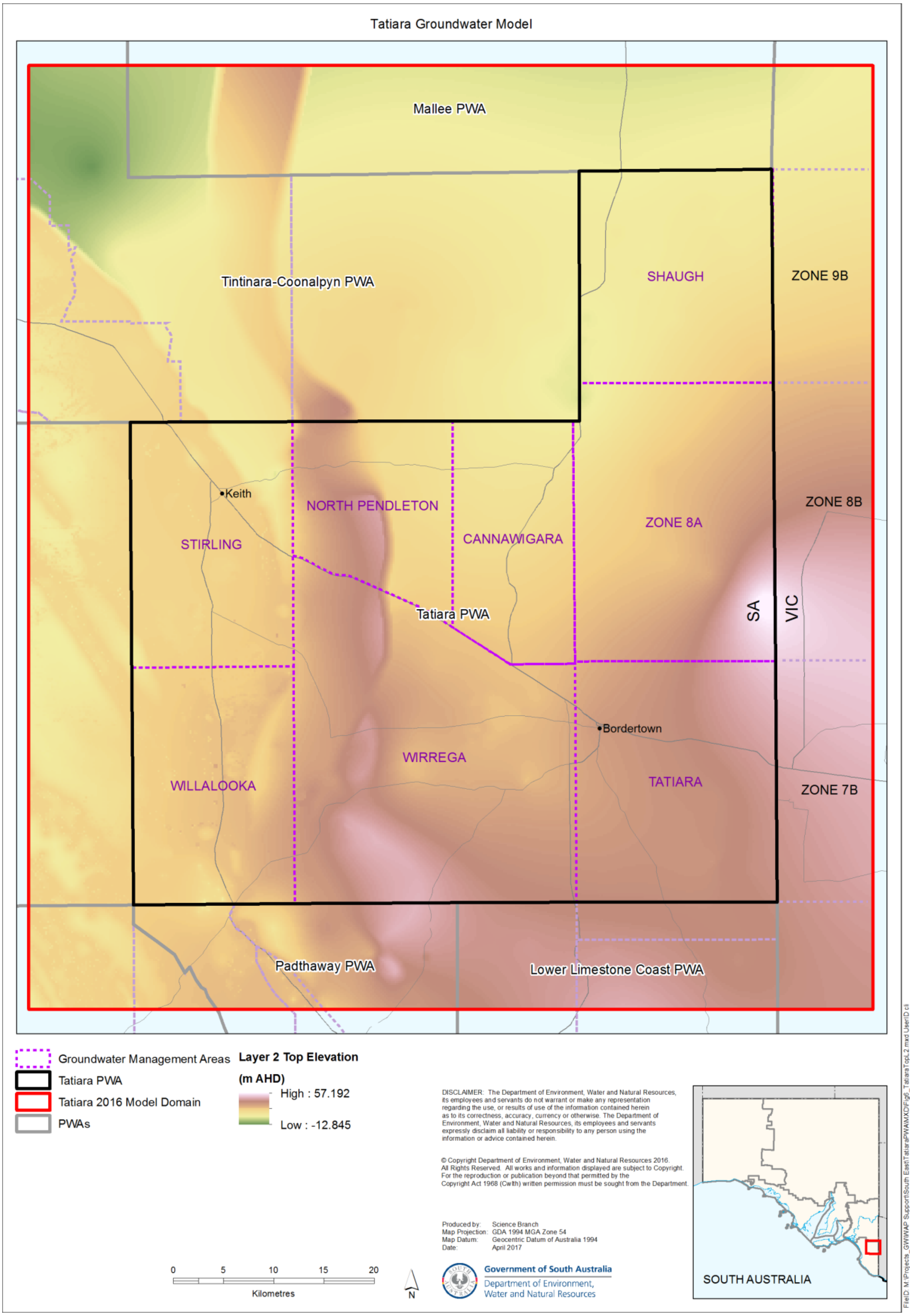

Figure 3.3. Top elevation of model layer 2 (m AHD)

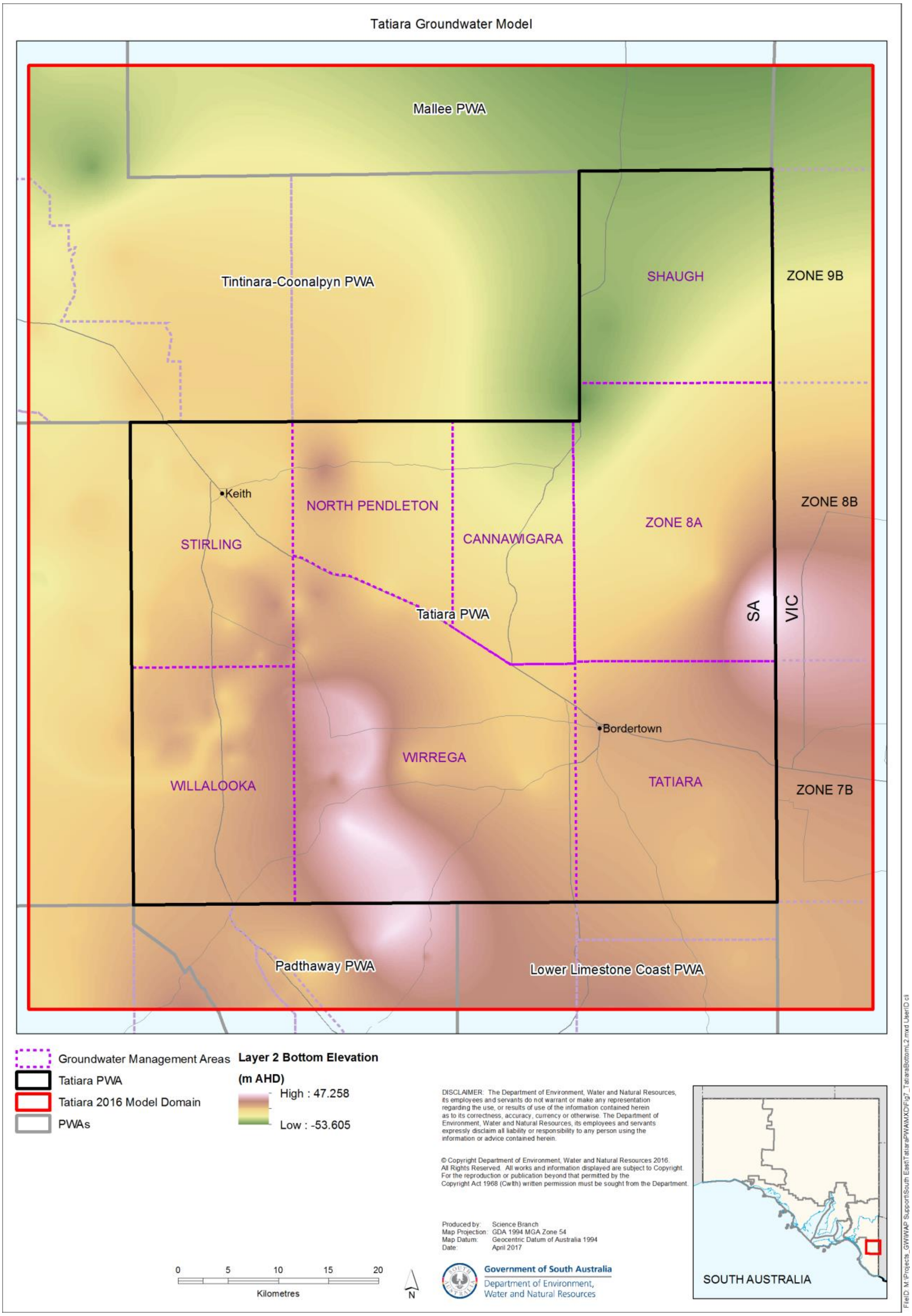

Figure 3.4. Bottom elevation of model layer 2 (m AHD)

3.4 Hydraulic parameters

The hydraulic parameter zones used in the final calibrated models are shown in Figure 3.5 and Figure 3.6. These were initially zoned based on surface geology data in combination with regional flow patterns and the hydrogeological framework presented earlier. During calibration, it was found that more zones were needed to achieve a better match to the observed water levels. Additional zones were created if, for example, the model was consistently overestimating or underestimating the water level for a particular area.

The initial parameter values were based on aquifer test data in combination with previous modelling studies (Wallis and Middlemis, 2007; Wood, 2011; Wood, 2016). They were then varied during calibration using an automated approach (i.e. PEST; see Section 4 for more details). Figure 3.5 and Figure 3.6 show the final horizontal hydraulic conductivity (K_h) for model layers 1 and 2 respectively using the values from Model B (see Chapter 4 for explanation of Models A, B and C). The vertical anisotropy (K_v: K_h) is set to the conventional value of 1:10 and was not varied in calibration. The parameter zones and values are largely the same between the two layers, except that in layer 2 the Padthaway Formation is replaced by the Bridgewater/Coomandook Formation to the west, and the Bridgewater Formation is replaced by the Murray Group limestone in the transition zone (defined by the steep hydraulic gradient towards the west, see previous description). Figure 3.5 also shows the model specific yield (S_y) values for model layer 1. The specific yield for layer 2 is not shown herein because MODFLOW treats the majority of layer 2 as a confined aquifer (since the head is generally above the top elevation of the layer) and therefore uses specific storage (S_s) instead. A conventional value of 1E-5 m^{-1} is adopted for specific storage for the entire model. Specific storage was found to be insensitive during the early stages of transient calibration and hence was not included in the subsequent calibration processes. The final ranges of model hydraulic parameters for each formation are summarised in Table 3.2.

Transmissivity values derived from aquifer tests on the coastal plain within the model domain range from 190–14 040 m^2/d with a median and mean of 2850 and 3837 m^2/d respectively (n=24 from a range of sources including Stadter and Love, 1987; Stadter, 1989; and Harding, 2012). Transmissivity values derived from aquifer tests on the Mallee highland within the model domain range from 224 to 4674 m^2/d with a median and mean of 1100 and 1263 m^2/d respectively (n=13 from a range of sources including Stadter and Love, 1987; Stadter, 1989; Stewart, 1990, Lawrence, 1975, Mustafa and Lawson, 2002; and Harding, 2012). When divided by plausible saturated aquifer thicknesses these transmissivity values convert to similar ranges to those implemented in the modelling investigation (e.g. a transmissivity value of 10 000 m^2/d divided by an aquifer thickness of 10 m results in a hydraulic conductivity value of 1000 m/d).

Only four Sy values have been reported within the model domain and include 0.035, 0.08, 0.13 and 0.24 (Stadter, 1989 and Harding, 2012). Stadter (1989) reported multiple aquifer test interpretations showing a possible range in S_y from 0.006 to 0.27 but ultimately adopted four final values (0.01, 0.06, 0.13 and 0.15) within the MGL of Border Zones 2A–8A. This limited dataset was used as a guide for determining plausible ranges and adopted values within the model. Previous modelling efforts have applied S_y values of 0.15 (Wood, 2011) and 0.2 (Wallis and Middlemis, 2007) within the Tatiara and Padthaway PWAs respectively. Further discussion of parameter values is found in Sections 4 and 5.

Table 3.2 Combined final value ranges of hydraulic parameters for Models A, B and C

	Layer	Coastal plain	Transition zone	Mallee highlands
Padthaway Formation	1	K_h: 143–1000 S_y: 0.1–0.2	-	-
Bridgewater/Coomandook Formation	1 & 2	K_h: 12–300 S_y: 0.1–0.2	K_h: 13–300 S_y: 0.1–0.2	-
Murray Group Limestone	1 & 2	-	K_h: 3–19 S_y: 0.15	K_h: 14–91 S_y: 0.19–0.2

*K_v = 0.1*K_h (m/d); S_s = 1E-5 m^{-1}.*

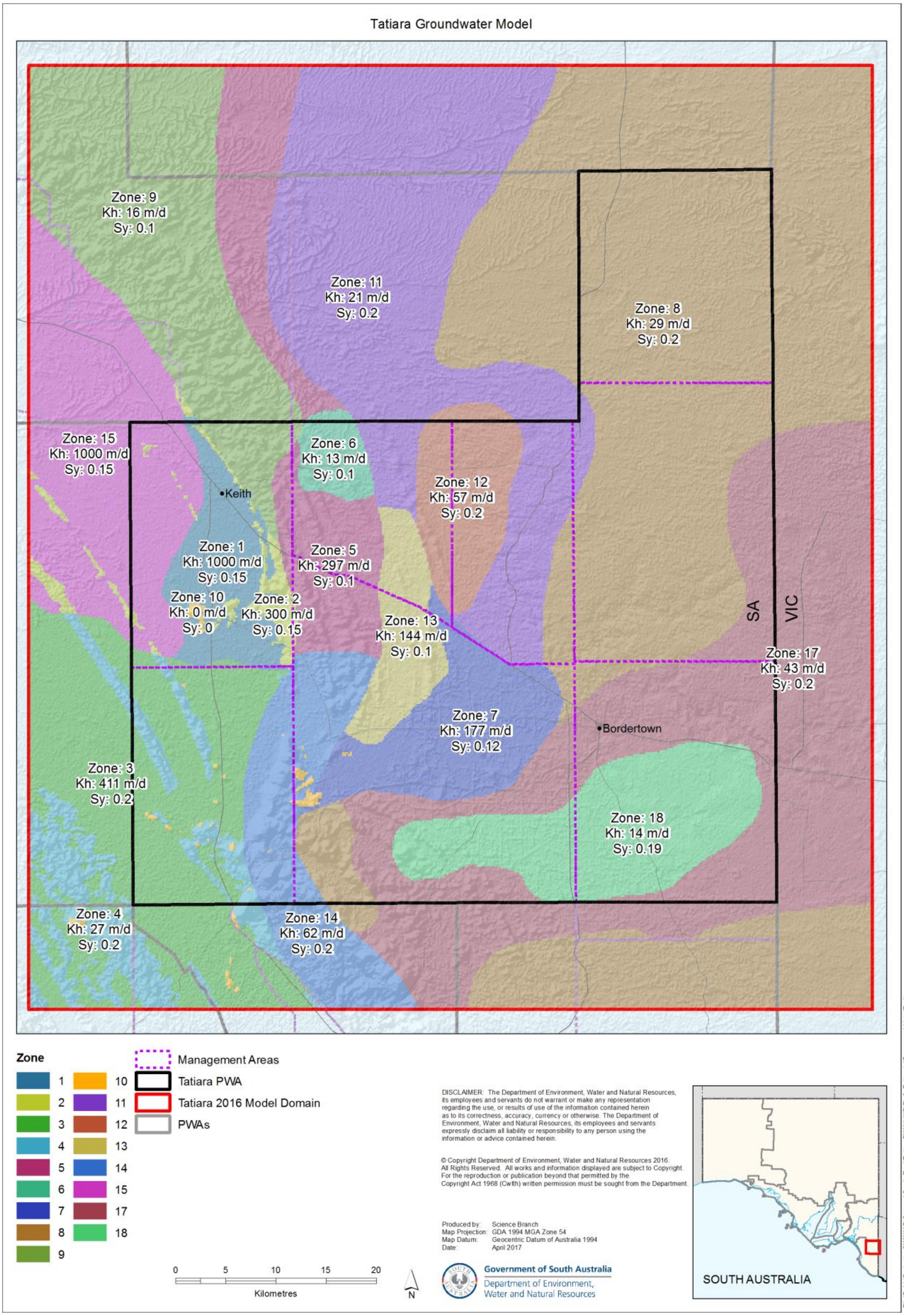

Figure 3.5. Horizontal hydraulic conductivity (m/d) and specific yield values for layer 1 zones (Model B values)

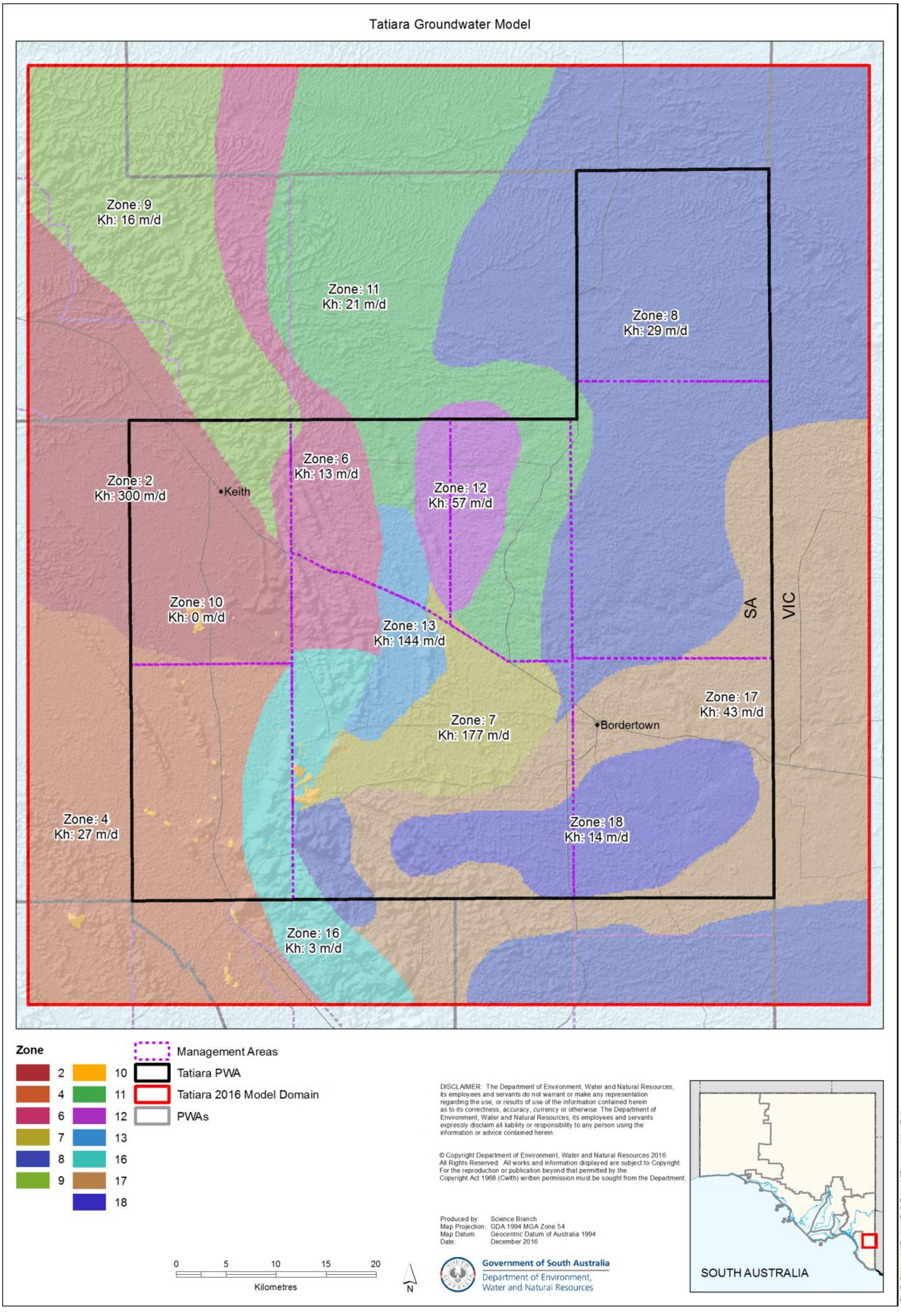

Figure 3.6. Horizontal hydraulic conductivity (m/d) values for layer 2 zones (Model B values)

3.5 Boundary conditions

3.5.1 Regional flow

The potentiometric surface shows that the regional flow direction is generally from east to west (Figure 2.3). Therefore the General Head Boundary (GHB) condition is implemented on the eastern and western model domain boundaries to represent regional inflow and outflow respectively (Figure 3.7). The northern and southern model domain boundaries are approximately parallel with the flow direction and therefore assigned as no-flow boundaries and in effect, the basement outcrops are also no flow boundaries since they are given hydraulic conductivity values of zero (Figure 3.7). In addition, the bottom of layer 2 is set up as a no-flow boundary, which assumes there are no significant vertical fluxes to or from the underlying Ettrick Formation aquitard and upper clay units of the Buccleuch or Renmark Groups.

A simplified transient GHB is adopted in the model. Two potentiometric surfaces were created from the observations for the model domain, one for 1984 and one for 2015. The 1984 surface was used to assign heads to the GHB for the period 1985–94. The GHB head is held constant during this period which is consistent with stable hydrographs near the GHBs. For the period 1995–2015, the GHB head declines linearly from the 1984 value to the 2015 value, mimicking the falling hydrograph trends particularly in the west (with very little change in the east).

GHB conductance is directly proportional to hydraulic conductivity, cell width and saturated thickness, and inversely proportional to distance. For simplicity, a uniform hydraulic conductivity of 100 m/d is assumed for the Padthaway Formation and Bridgewater Formation to the west, and 30 m/d for the Murray Group Limestone to the east. The cell width is the same as the cell size dimension, which is 200 m. The saturated thickness is calculated as the difference between GHB head and cell bottom elevation for layer 1 (cell thickness is used as the saturated thickness for layer 2), ranging from 3 to 50 m to the west and 21 to 54 m to the east. As the potentiometric surface value at the GHB cells are used directly as the GHB heads, a distance of 1 m is adopted. These result in GHB conductance values ranging from 60 000–1 000 000 m^2/d in the west and from 126 000–324 000 m^2/d in the east. With such high conductance values, the GHBs function similarly to constant head cells and changing the conductance does not significantly impact the model results unless it is reduced to a much smaller order of magnitude (e.g. less than 1000), hence GHB conductance was not included in the final calibration process.

3.5.2 Groundwater evapotranspiration

The Tatiara model uses potential groundwater evapotranspiration (ET) and extinction depth to determine actual groundwater ET. Potential groundwater ET is defined as the amount of groundwater ET that would have occurred if the water table is at the land surface. The FAO56 data from the 15 weather stations within the model domain is averaged and used as the potential groundwater ET for the model. The steady state model adopts a potential groundwater ET rate of 1209 mm/y, averaging from the 10 years before the transient simulation. Seasonal potential groundwater ET is used for the transient model, ranging from 278–359 mm for winter and 783–967 mm for summer.

The extinction depth is the depth at which groundwater ET ceases. Groundwater ET is assumed to decrease linearly from the potential rate at the land surface to zero at the extinction depth. The model adopts a conventional value of 2 m for the extinction depth and has not been varied or investigated further. As shown in Figure 3.8, the areas of greatest groundwater ET occur in the far west of the model domain which is supported by the observed shallow groundwater with relatively high salinities found in that area as well as ephemeral surface water bodies that are likely to be groundwater dependent, i.e. groundwater discharge areas (see Figure 2.2).

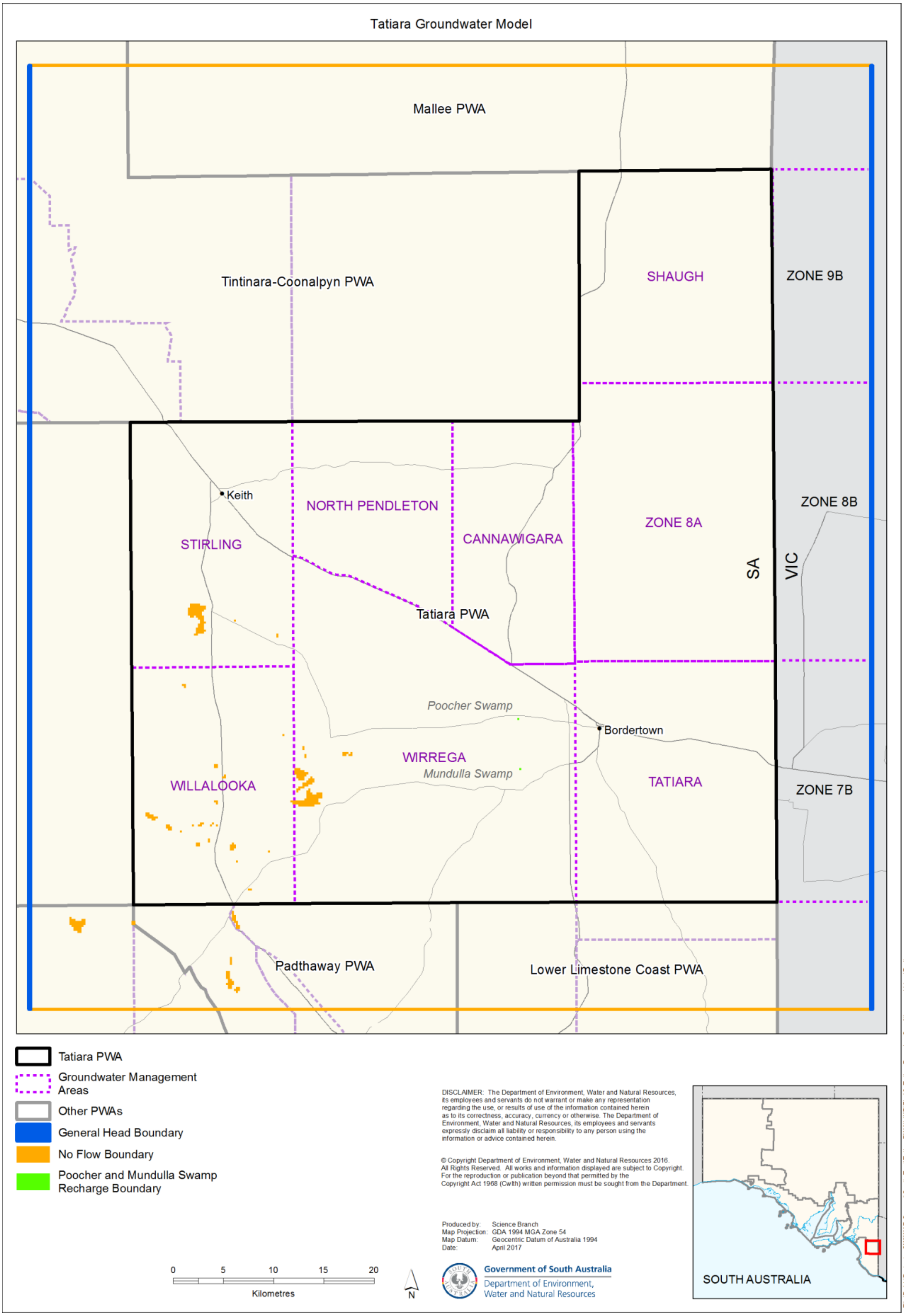

Figure 3.7 Tatiara model boundary conditions

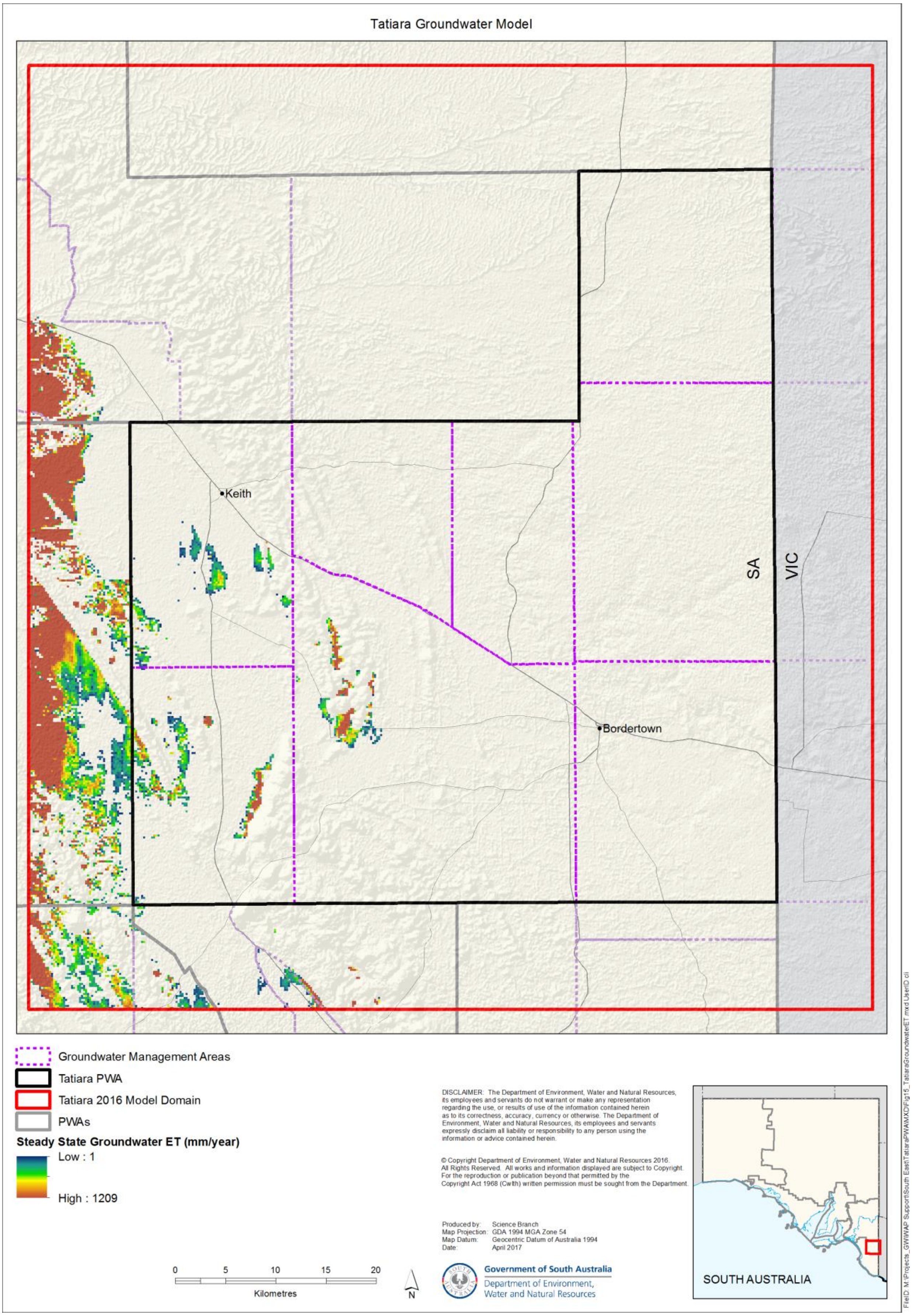

Figure 3.8 Distribution of steady state groundwater ET for Model B

3.5.3 Upper South East recharge model

Diffuse rainfall and irrigation recharge has been applied using averaged monthly outputs for each stress period from the LEACHM recharge model for the Upper South East (Morgan et al., 2017). This model directly simulates the 1D unsaturated zone transport of water based on soil, landuse, rainfall, potential ET, crop type, irrigation and other factors and represents the gross recharge passing through the unsaturated zone. The unsaturated fluxes below the modelled soil column for 681 unique combinations of these factors were distributed across an area that includes the Tatiara groundwater model domain. Two depth profiles were used, with 5 m profiles applied to the coastal plain and 20 m profiles for the Mallee highlands. Long warm up periods were applied to ensure that the initial conditions found in the deep unsaturated zone did not influence the fluxes draining from the bottom of the 20 m profile (see Morgan et al., 2017 for more detailed description). The recharge signal from the 20 m profile was also damped (i.e. no seasonal variability) which is appropriate for areas where there are thick unsaturated zones.

For the majority of the model, the gross recharge can be considered equivalent to the net recharge (where water tables are relatively deep) as they include irrigation recharge but exclude direct groundwater ET (which only occurs where water tables are shallow and is approximated within MODFLOW as described in the following section). A detailed comparison between the LEACHM recharge estimates and those of other field based approaches can be found in Morgan et al., (2017) while a brief comparison is outlined below. Point recharge at the Poocher and Mundulla Swamps is simulated using a different approach, as described in Section 3.5.2.2.

Comparison with the field-based recharge estimates from selected GMAs are shown in Table 3 and include all landuse and soil types assessed by the respective authors and all methods applied at each site. The LEACHM results have been averaged over the 1985–2015 time period while the field based approaches are representative of the time of analysis or for some time prior, depending on the length of analysis and method implemented. The range of LEACHM recharge estimates for the Sherwood GMA, Tatiara GMA and northeastern parts of the Lower Limestone Coast PWA compare well with the field based estimates. The lower mean values in the Sherwood and Tatiara GMAs are due to the LEACHM averages including larger areas of native vegetation and/or dryland agriculture than those represented by the field estimates. Similarly the LEACHM estimates from Stirling and Padthaway Flats GMAs have greater areas of dryland agriculture represented while the field based methods are more representative of irrigated areas. The higher mean values for the areas in the northeast of the Lower Limestone Coast PWA are due to large areas of irrigated crops being under-represented by the field based estimates.

Table 3 Comparison between field based point estimates and LEACHM estimates of average recharge (mm/y).

	Field-based recharge estimates				**LEACHM recharge estimates (1985–2015)**			
GMA	*No. of estimates (No. sites)*	*Mean*	*Range*	*Reference*	*Unique combs.*	*Mean*	*Median*	*Range*
Sherwood	7 (7)	14.9	7–30	Leaney, 2000; Wood, 2011	24	2.5	0.6	0.3–28
Tatiara*	26 (11)	25.9	0.4–85.9	Stadter, 1989; Wohling, 2007	95	19.8	17.9	0.1–85.2
Stirling	76 (9)	392.1	2.9–1727	Wohling, 2007	38	109.5	37.5	0.4–542
Padthaway Flats	17 (7)	440.0	80–1750	Harrington et al., 2006	80	63.7	46.3	0.5–489
NE Lower Limestone Coast	52 (22)	19.5	0.5–51	Stadter, 1989; Wohling, 2007; Wood, 2011	92	26.2	28.2	0.3–93

*Note that the small area south-west of Bordertown where flood irrigation occurs has been excluded from the LEACHM statistics with recharge values of 245–482 mm/y

The upper range values for field-based estimates for Stirling and Padthaway Flats GMAs are much higher than the LEACHM estimates and are representative of specific sites under flood irrigation. These high recharge values estimated by Harrington et al. (2006) and others by Wohling (2007) could be facilitated by particularly transmissive soils, which are not represented within the generalized soils dataset used in LEACHM (i.e. no highly transmissive soils are represented). Additionally, the variability that exists in site specific irrigation efficiency is not represented in the LEACHM estimates. LEACHM recharge under the flood irrigation has been calibrated to be close on average, to an average of 403 mm/y as estimated by Wohling (2007) rather than to represent a wide range of values (resulting from a range of irrigation practices).

Despite the complexity of the LEACHM recharge model described above (and in Morgan et al., 2017), there is still a considerable amount of uncertainty in these recharge estimates (which is also true for all other recharge estimation techniques). Therefore recharge was included in the calibration process and allowed to vary by ±50%. Due to computational constraints, it was impractical to calibrate the recharge value for each model cell for each stress period. Hence simplification was made by calibrating recharge multipliers instead. In MODFLOW, the multiplier cannot vary spatially but can vary between stress periods. The spatial distribution of calibrated recharge (incorporating the multiplier) for steady state is shown in Figure 3.9 and represents the 1984/85 conditions. The average recharge over the transient calibration period (1986–2015) is shown in Figure 3.10.

The predicted flow rates for Nalang and Tatiara Creeks described in Section 2.2.4 have been used directly to approximate point recharge based on the Bordertown rainfall occurring during the Tatiara model calibration period and future periods. This point recharge is applied to a number of model cells in the vicinity of the runaway holes in the Poocher and Mundulla Swamp areas and are evenly distributed across the winter stress period. Poocher Swamp recharge was focused on a smaller number of cells in order to approximate the more rapid aquifer response in nearby observation wells (i.e. WRG032) while Mundulla Swamp did not have observation wells near enough to show such large recharge signals.

3.5.4 Groundwater extraction

As discussed in Section 2.4, the groundwater extraction datasets have been developed for the Tatiara model domain using a combination of estimated and metered groundwater extraction data. The uncertainty of estimates based on theoretical crop requirements has resulted in the development of three alternative extraction datasets. These apply scaling factors of 1.4, 1.6 and 1.8 to the groundwater extraction occurring on the coastal plain (where flood irrigation is common) prior to the start of metered data. These three variations in groundwater extraction are shown previously in Figure 2.6 and refer to Model A (green symbols), Model B (orange symbols) and Model C (dark blue symbols) for scaling factors 1.4, 1.6 and 1.8 respectively.

Within the models, all extraction wells were screened 50% within layer 1 and 50% within layer 2 because licensed extraction wells commonly have open-hole completions. This is particularly the case on the coastal plain where Quaternary limestone aquifers can be difficult to differentiate while each formation potentially contains good yielding sections (i.e. Padthaway Formation overlying Bridgewater or Coomandook Formations). The proportion of extraction volume taken from each layer is dependent on the transmissivity of that layer calculated in based on initial conditions.

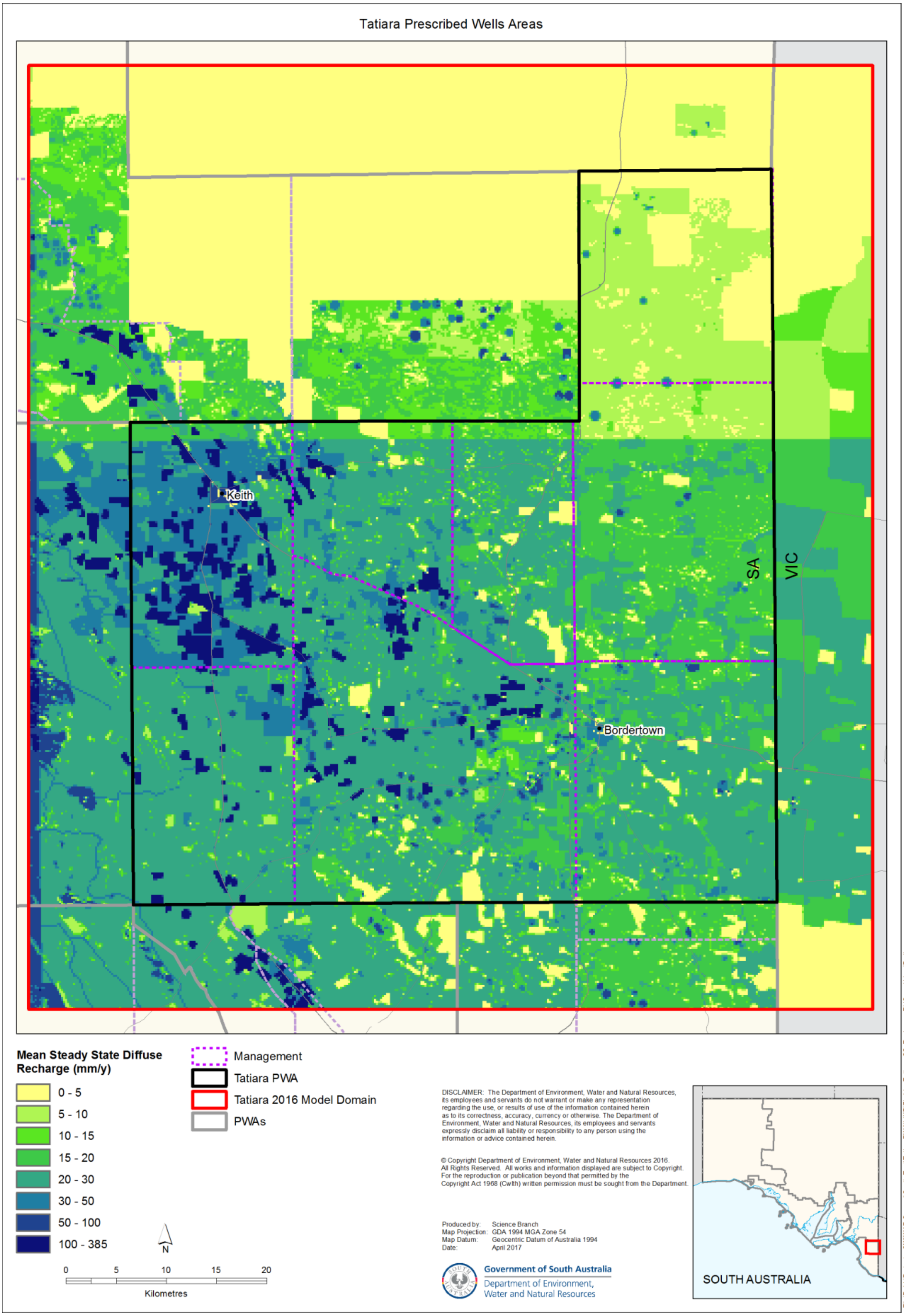

Figure 3.9 Diffuse recharge for steady state after applying the calibrated multiplier of Model B

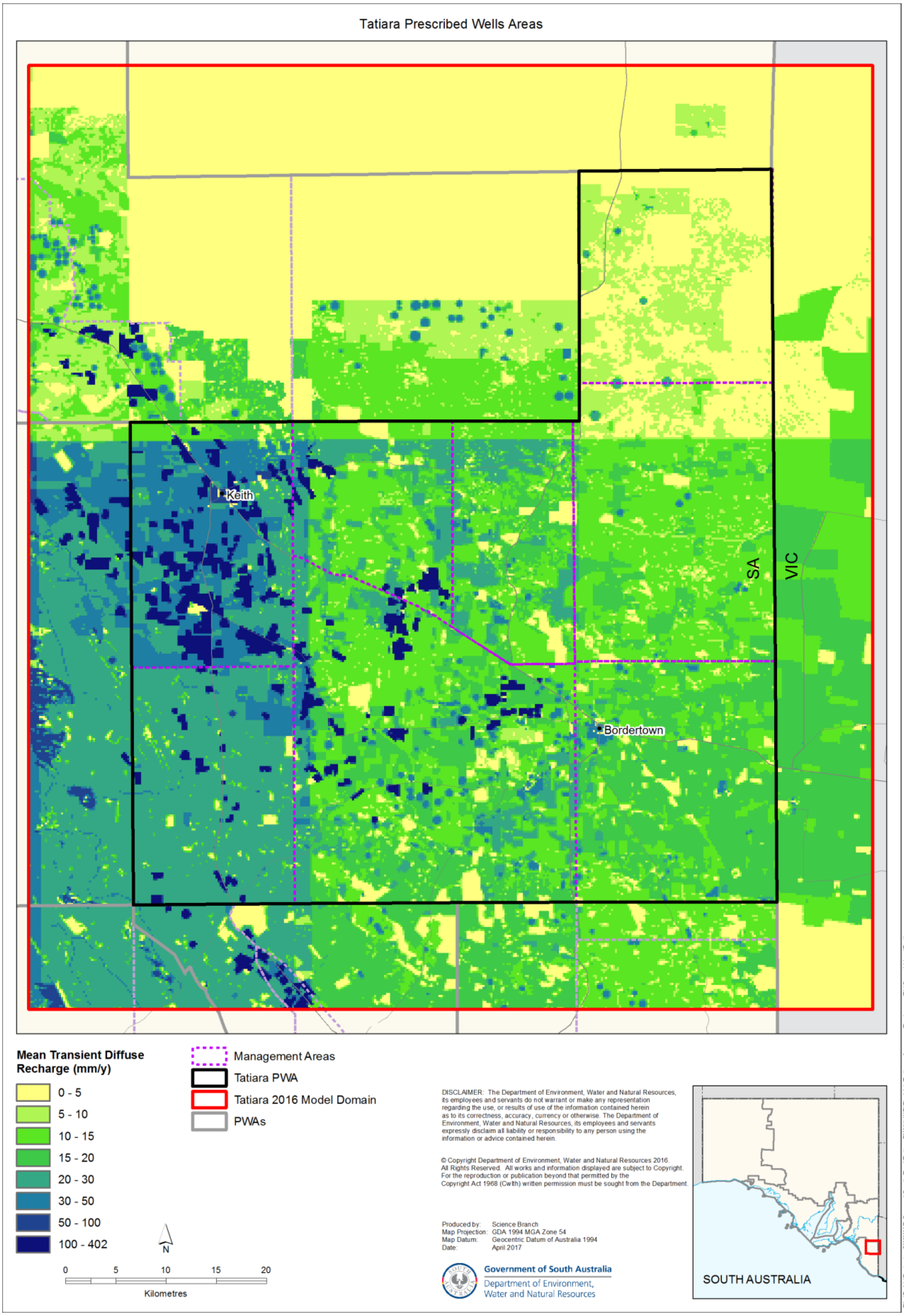

Figure 3.10 Average transient diffuse recharge (1986 to 2015) after applying recharge multipliers of Model B

3.6 Initial conditions and stress periods

The initial heads for the steady state model were based on a surface derived from observed groundwater levels just prior to 1985, and the results from the steady state model were used as the initial conditions for the transient model.

The model consists of 62 stress periods, with the first stress period simulating the steady-state condition and the remaining stress periods simulating transient conditions. It is acknowledged that true steady-state condition rarely exists in reality as inputs such as rainfall and stresses such as extraction are continuously changing. However, a steady state model is required to provide the initial conditions for the transient model. Since cumulative deviation from mean rainfall was relatively stable during the ten years prior to 1985 and little is known about groundwater extraction prior to the major expansion in the 1980s, the period of 1/4/1984 to 31/3/1985 was selected as a relatively steady-state period. The transient period is from 1/4/1985 to 30/9/2015 and has six-monthly seasonal stress periods (i.e. summer and winter). Based on the monthly rainfall distribution, winter is defined as the beginning of April to the end of September, and summer is defined as the beginning of October to the end of March. These periods are believed to appropriately capture the irrigation season in summer and wetter period during winter. The location of observation wells are shown in Figure 3.11 and have been grouped by the number of stress periods where they contain observations.

3.7 Zone budgets

Zone budgets were set up for each GMA for individual mass balance analysis. In addition, the hydrogeological zones from Harrington and Currie (2008) were incorporated to separate the zone budget into coastal plain and Mallee highland areas which also divides parts of the Cannawigara, North Pendleton and Wirrega GMAs. Although Stirling and Willalooka are also intersected by the hydrogeological zone boundary, the intersected portion is too small to report separately and therefore they are reported as whole GMAs. The model budget zones are shown in Figure 3.12.

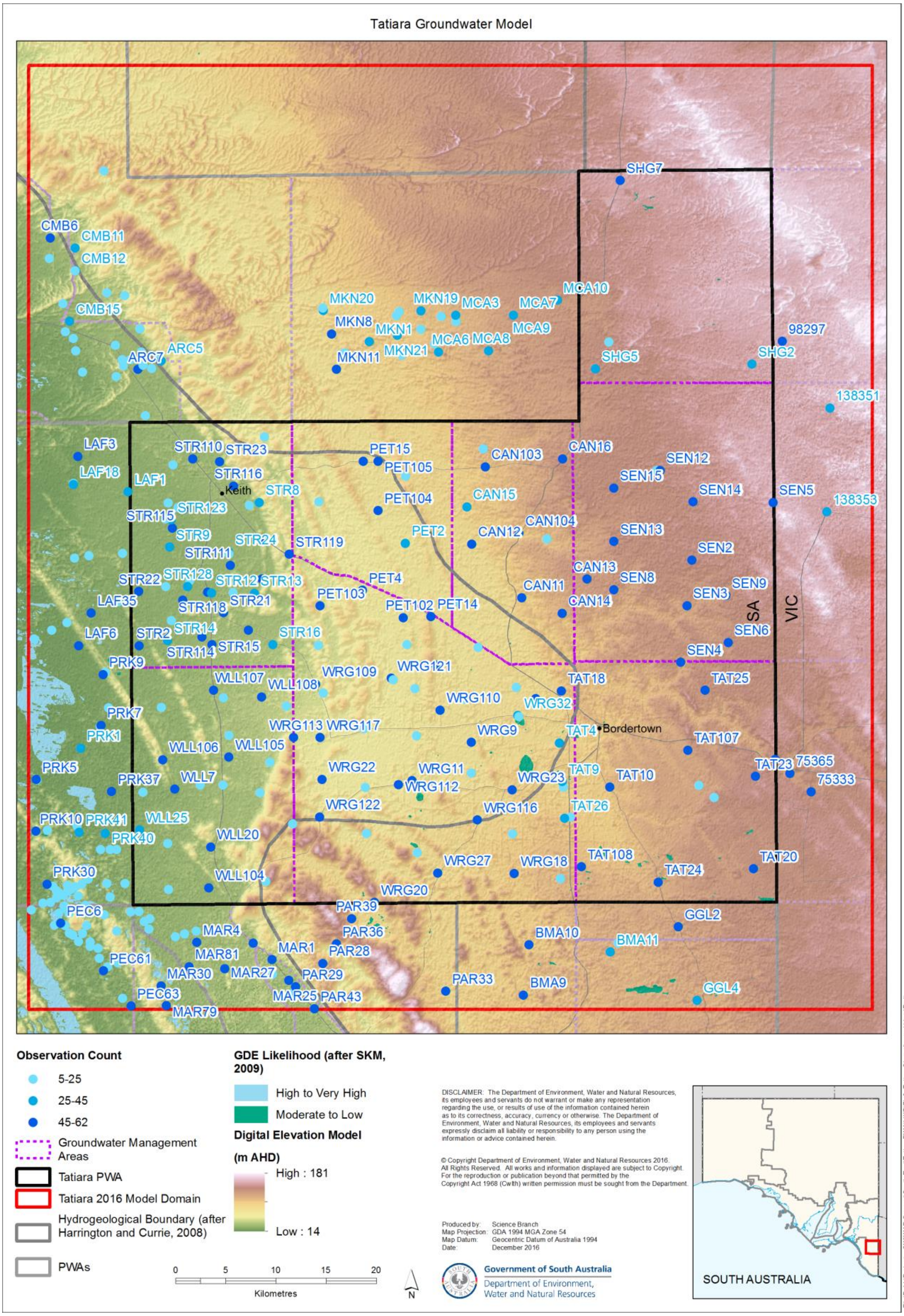

Figure 3.11. Observation wells showing the number of stress periods where groundwater level data is available

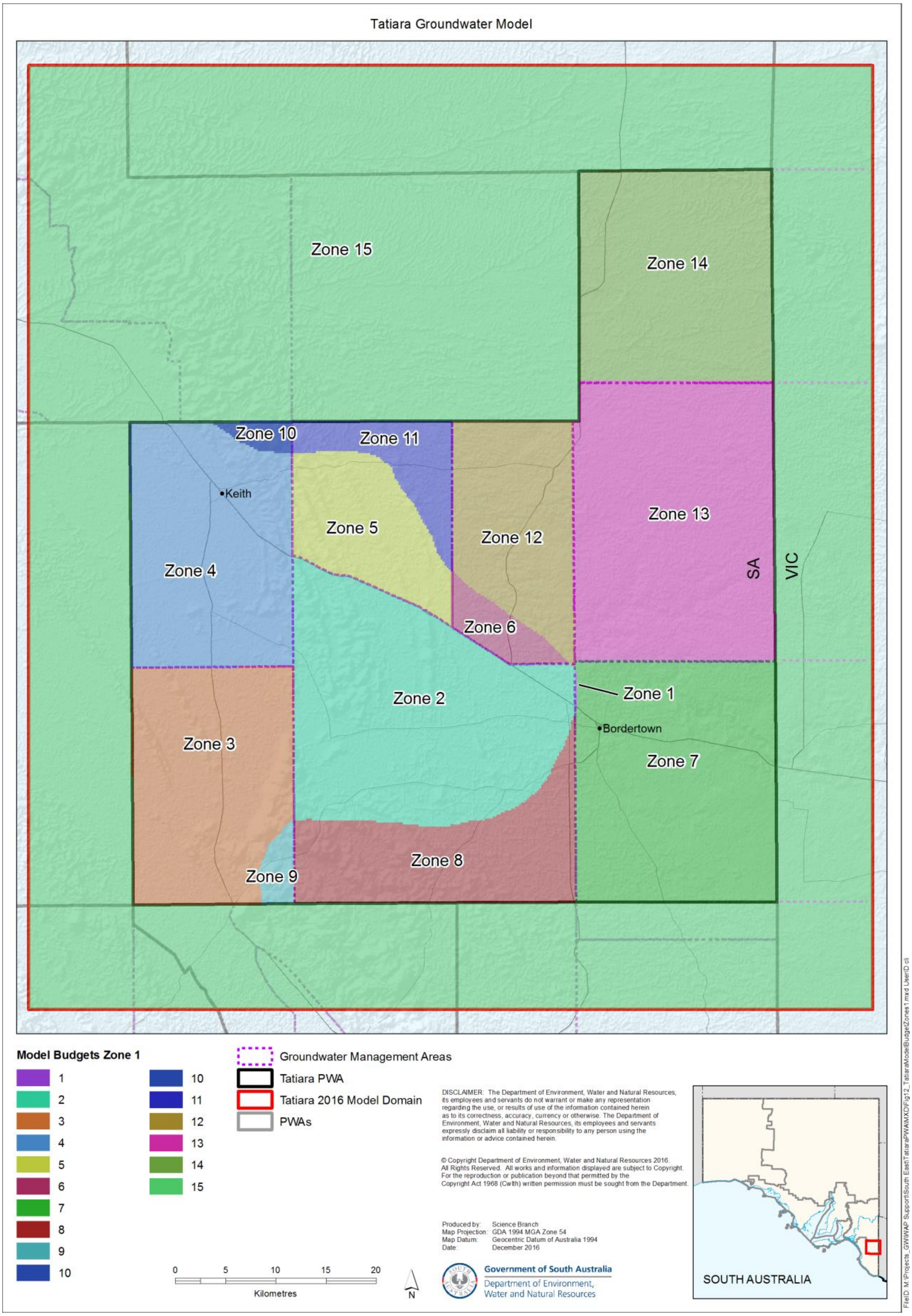

Figure 3.12. Model budget zones with division between hydrogeological zones 2–3 of Harrington and Currie (2008)

4 Model calibration

4.1 Overview

4.1.1 Calibration methodology

Model calibration is a process in which model parameter values are altered within reasonable bounds so that the simulated groundwater system more closely reflects the observed groundwater system. This is a partially subjective process that can be aided by the use of automated parameter estimation software such as PEST (Doherty, 2013). In this model we have used PEST as a tool to help in the calibration of both steady state and transient models and have then made manual alterations based on an assessment of parameter sensitivity, model behavior and expert opinion. The model has been calibrated primarily to hydraulic heads with some regard to salinity dynamics in the west where evapotranspiration of shallow groundwater is known to have occurred (i.e. areas of high groundwater ET should coincide with areas of higher groundwater salinity). Three groundwater models have been calibrated which have different historical pumping datasets (i.e. different scaling factors applied to the coastal plain crop requirement estimates). These models are referred to as Models A, B and C as discussed in Sections 2.4 and 3.5.4.

PEST allows parameter estimation to be performed in a systematic and automated manner using gradient-search algorithms to minimize an objective function. For the PEST runs conducted for this study, the objective function (phi) was defined as the sum of squared weighted residuals of hydraulic head (i.e. the difference between simulated and observed head in all observation wells for all appropriate time periods) and is a measure of goodness of fit for the inverse problem. Although PEST is an automated approach, calibration was still undertaken on an iterative basis by adjusting PEST options, target weights, parameter zones and both initial and rationalised parameter values.

4.1.2 Calibration targets

There were no elaborate weighting schemes applied to the observations, apart from using six-monthly averages for each stress period as suggested by Rumbaugh (2016) and a reduction in the weight given to selected wells. For the steady state and transient models all observation targets have a weight of 1, except for those that show a non-equilibrium response to post-clearance recharge, including BMA9, BMA10, BMA11, PAR33, PAR36, PAR39 and WRG20. Observations from these wells have been given a lower weighting of 0.1 because their hydrographs showed rising trends of up to 5 m from 1985 to approximately 2005, before stabilizing and starting a slow decline. This is believed to be due to a transitional shift towards higher recharge rates and a new dynamic equilibrium after land clearance which is not simulated in the recharge model (i.e. constant landuse) nor applied in MODFLOW. Furthermore these wells (with the exception of WRG20) are located outside of the Tatiara PWA and so it was not considered critical to simulate this behavior.

4.1.3 Calibration performance

The scaled root mean squared (SRMS) error for the model was 2.7, 2.8 and 2.9% with a root mean squared (RMS) error of 1.62, 1.67 and 1.75 m and an absolute residual mean of 1.14, 1.20 and 1.23 m for Models A, B and C respectively (by comparison with 9781 observations from 312 wells). The reduction of phi for the final PEST runs are shown in Figure 4.1 and it can be seen that there were good improvements made in the model fit even at this late stage (earlier model versions had transient model phi values on the order of 100 000). The final models were slightly de-calibrated after rounding and rationalization of some parameter values resulting in a slightly larger phi value. However these values are more appropriate for reporting and have been scrutinized with respect to hydrograph behavior and hydrogeological understanding.

The following sections describe the details of model setup, steady state and transient calibration approaches and objectives. Meanwhile, Section 5 gives a discussion of parameter sensitivity and a number of types of model uncertainty.

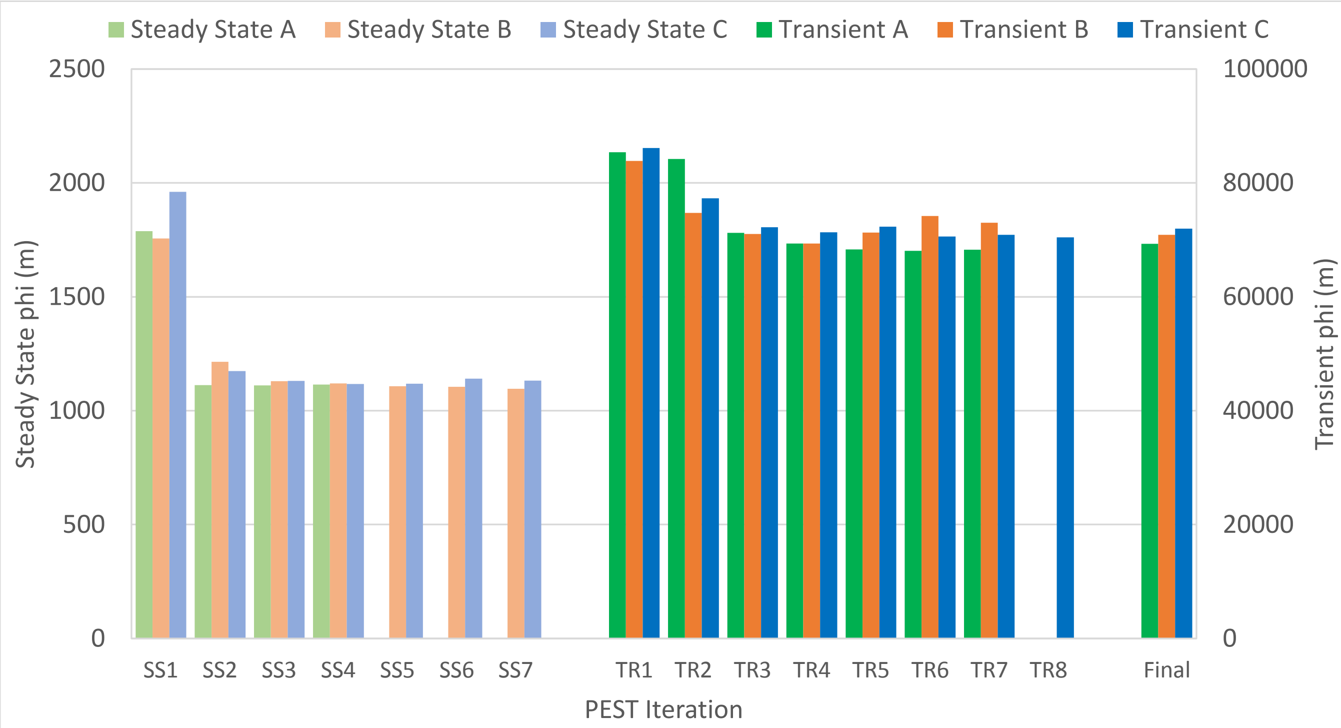

Figure 4.1. Phi reduction during final PEST runs

4.2 Steady state calibration

Steady state calibration is undertaken to develop a broad-scale hydraulic conductivity distribution and an appropriate initial recharge multiplier to gross recharge estimates of Morgan et al. (2017). Dynamic stresses and storage effects are excluded from steady state calibration by definition. The parameters that were included in the calibration are hydraulic conductivity and one recharge multiplier. Here the steady state model simulates the conditions just prior to and including the 1984/85 period (including extraction), which are assumed to be relatively stable as a starting point for the transient model. The initial parameters, the upper and lower bounds for each parameter, and the adopted parameters are shown in Table 4.1. The initial parameters and upper and lower bounds are reasonable estimates based on previous modelling work (e.g. Wood, 2011), aquifer test data and conceptual understanding.

Table 4.1 Steady state PEST parameter setup

	Zone or stress period	Lower bound	Upper bound	Initial value	PEST value			Adopted value for initial transient models*		
					A	*B*	*C*	*A*	*B*	*C*
Hydraulic conductivity (m/d)	1	1	1000	400	951	**1000**	**1000**	951	900	900
	2	1	300	200	**300**	**300**	**300**	200	200	200
	3	1	1000	100	42	227	57	42	227	57
	4	1	300	75	29	53	50	29	53	50
	5	1	300	75	80	**300**	124	80	200	124
	6	1	200	30	42	35	50	42	35	50

	7	1	200	30	85	134	127	85	134	127
	8	1	200	30	42	58	56	42	58	56
	9	1	300	75	30	41	38	30	41	38
	11	1	200	30	26	37	33	26	37	33
	12	1	200	30	48	82	60	48	82	60
	13	1	200	30	154	**200**	**200**	154	150	150
	14	1	300	75	38	70	73	38	70	73
	15	1	1000	400	370	**1000**	378	370	900	378
	16	1	200	30	25	24	21	25	24	21
	17	1	200	30	57	91	70	57	91	70
	18	1	200	30	12	17	16	12	17	16
Recharge multiplier	1	0.5	1.5	1	0.96	1.30	1.27	0.96	1.30	1.27

* These values are not final. They were adopted as the initial values for transient calibration and further modified during the iterative PEST and rationalisation process.

A scatter plot comparing observed with simulated hydraulic heads for the steady-state stress period (using final calibrated parameters discussed in the following section) is shown in Figure 4.2. The observation data from outside the Tatiara PWA has also been included as these data were generally given the same weights as those within the PWA. The model slightly underestimates head observations in the coastal plain while slightly overestimating them in the highland transition and Mallee highlands. There are a number of outliers which are poorly matched but these are located in areas where there is considerable uncertainty regarding the structure of the hydrogeological units (near Mt Monster and basement outcrops) or non-equilibrium processes occurring (i.e. Naracoorte Ranges). Overall the calibration is considered to be very reasonable for use as initial conditions in the transient model.

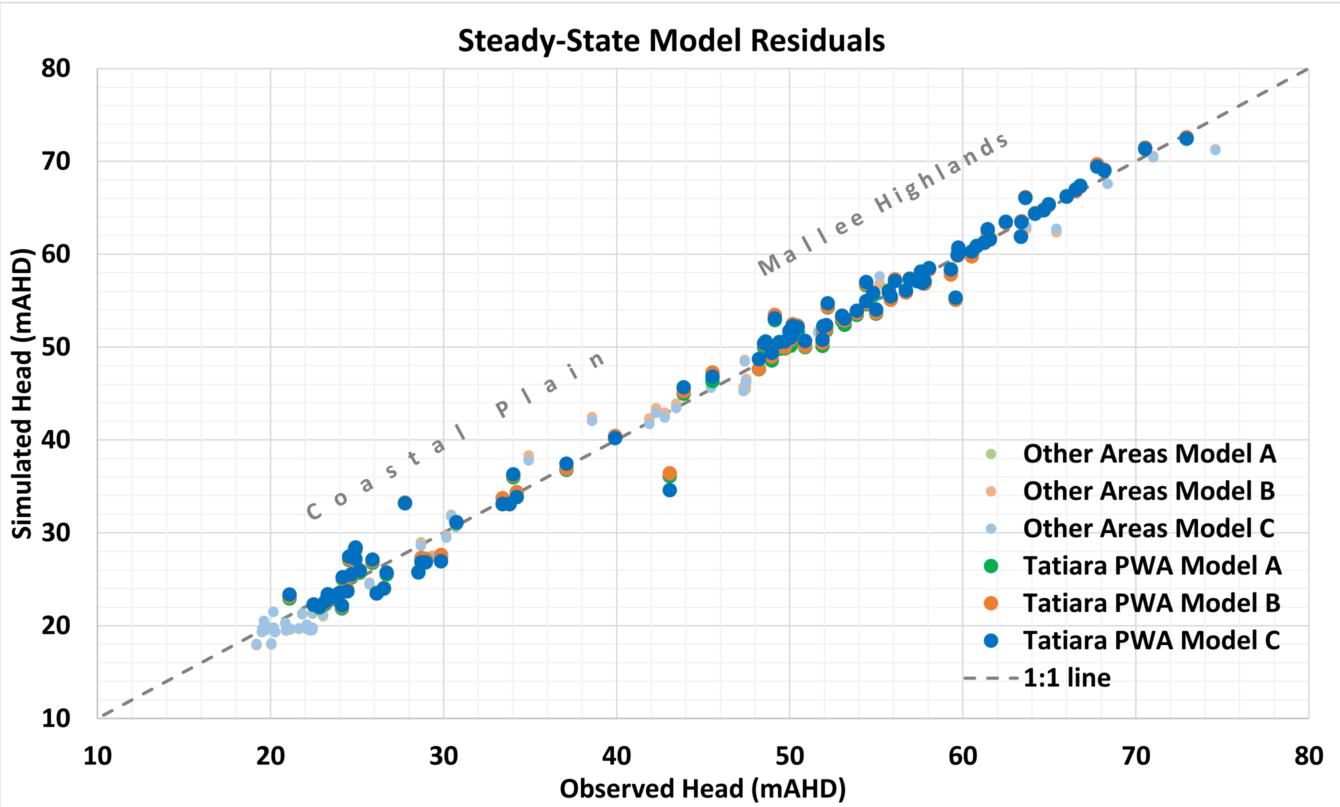

Figure 4.2. Steady-state scatter of observed vs simulated heads within the Tatiara PWA and other model area

4.3 Transient calibration

Transient calibration is undertaken to further develop the hydraulic conductivity distribution and recharge multipliers in addition to storage parameters. Following the steady state model stress period (simulates the 1984/85 conditions) an additional 61 six-monthly stress periods were simulated finishing in the winter of 2015. The initial parameters, the upper and lower bounds for each parameter, final PEST values and the adopted parameters are shown in Table 4.2 for each of the three calibrated models. The initial parameters are based on the rationalized parameter values of the steady-state PEST run while the upper and lower bounds are unchanged.

The final PEST values for hydraulic conductivity were rounded to the nearest integer while the values of recharge multipliers were rounded to two decimal places. Many of recharge multipliers hit the upper (highlighted blue) and lower (highlighted green) bound (see Table 4.2) which could be due to the lag times estimated by the LEACHM modelling based on 5 m unsaturated zone profiles on the coastal plain (see discussion in Morgan et al., 2017) not aligning with actual depth to water (which varies across the area from approximately 5–15). These recharge multipliers are plotted for each stress period and each model in Figure 4.3A. It is clear that Model A and Model C oscillate between the upper and lower bound while the recharge multipliers of Model B generally find a place within the bounds. It is interesting to note that recharge multipliers in Model A frequently reaches the upper bound in winter stress periods while multipliers in Model C reach the upper bound in summer stress periods (and vice versa). This implies that Model A requires greater winter recharge and lower summer recharge which could be to increase the seasonal variability of groundwater levels to compensate for low extraction rates relative to the other models (i.e. coastal plain multiplier of 1.4). In contrast, Model C requires greater summer recharge and lower winter recharge which may be to lessen the influence on seasonal variability of higher extraction rates relative to the other models (i.e. coastal plain multiplier of 1.8). The recharge multipliers of Model B generally follow the direction of change away from 1 as Model C suggesting the need for less seasonal water level fluctuations but are on average very close to 1 until the late-1990s before declining to 0.5.

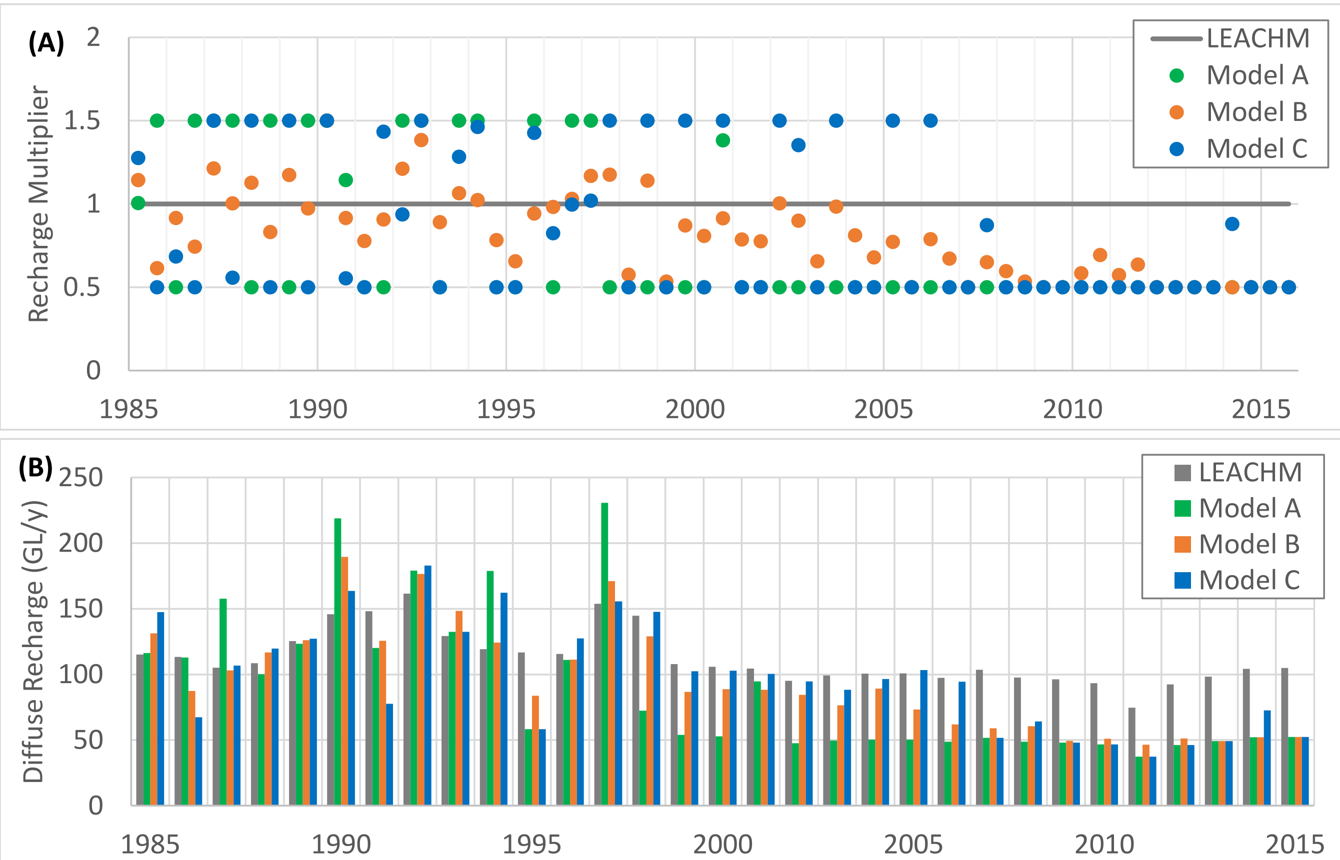

Figure 4.3. Calibrated recharge multipliers for all model stress periods (A) and total yearly diffuse recharge rates (B)

All three models show recharge multipliers approaching the lower bound of 0.5 towards the latter half of the calibration period. Total diffuse recharge volumes within the Tatiara PWA reduce from the LEACHM estimates of around 100 GL/y to model totals around 50 GL/y (Figure 4.3B). This general reduction to recharge below the values simulated by LEACHM appears to be necessary in order to match the declining groundwater level trends observed in the coastal plain (see later discussion in Section 4.3.1). It appears that the LEACHM recharge is an overestimate during this period while it may underestimate recharge in wetter periods.

The Sy values determined by PEST (see Table 4.2) were considered in many cases to be too low or too high (i.e. lower bound of 0.05 for Padthaway Formation or upper bound of 0.25 for Murray Group limestone). The zones reaching the lower and upper bound values were narrowed to 0.1 and 0.2 respectively since the model was relatively insensitive to these parameter values (see section 5.3). The impact of this change to 0.1 was slight reduction in the seasonal variation and declining trends of simulated hydrographs. For the change to 0.2, there was a slight increase in the seasonal variation and declining trends of simulated hydrographs in those zones. The SRMS change is less than 0.1% and the RMSE change is less than 0.1 m for each of the models. In addition, the hydrograph fits were not considerably poorer as a result but in some cases matched the behavior of observed data better. Hence it is considered reasonable to alter these parameter values as described.

The hydraulic conductivity values consistently reached the upper bound during the calibration process for a number of zones suggesting that the ideal value may be beyond these limits. This was the case for zones 1 and 15 representing the Padthaway Formation and zone 2 representing the underlying Bridgewater and Coomandook Formations which are located in and near the Stirling GMA. Seven aquifer tests have been reported within the Stirling GMA with transmissivity values ranging from 1580–6420 m^2/d (Stadter and Love, 1987). Transmissivity values for two wells elsewhere in the Padthaway Formation have been reported at 11 230 and 13 000 m^2/d (Mustafa and Lawson, 2002). If these values are divided by typical saturated thicknesses for layer 1 of say 5 to 10 m, then the hydraulic conductivity value of 1000 m/d can be justified. An alternative to these high K values would be to reduce recharge, including estimates of under flood irrigation and/or increase the thickness of layer 1. These hypotheses were not extensively explored (apart from varying recharge multipliers through calibration) but are further discussed below and in Chapters 5 and 7.

A series of scatter plots for each calibrated model comparing observed with simulated hydraulic heads for transient stress periods are shown in Figure 4.4. The observation data from outside the Tatiara PWA (shown as faded symbols) has also been included as these data were generally given the same weights as those within the PWA. The model again slightly underestimates head observations in the western part of the coastal plain (lower elevations) while slightly overestimating them in the eastern part (higher elevation) of the coastal plain adjacent to the Mallee highlands. There are a number of deviations away from the 1:1 line for hydrographs in the coastal plain (Figure 4.4). These observation wells are found in locations where there is considerable uncertainty regarding the structure of the hydrogeological units (i.e. near Mt Monster and other basement outcrops) and also in areas where non-equilibrium processes occurring (i.e. changing recharge rates in the Naracoorte Ranges). For example, simulated hydrographs for wells WRG109 and WRG113 show both an offset and poor trends when compared to observed hydrographs (see data points between observed 38 and 46 m AHD in Figure 4.4 and respective hydrographs in Appendix A found in Volume 2 of this report). Some other hydrographs such as WLL104 on the coastal plain (see observed water levels from 26 to 29 m AHD in Figure 4.4 and hydrograph in Appendix A found in Volume 2 of this report) are offset from the 1:1 line and are found in areas where there is again some uncertainty in the hydrogeological structure (i.e. thin and/or discontinuous layers). WRG32 data is located from observed 52–69 m AHD in Figure 4.4 and is seen to respond rapidly to point recharge at Poocher Swamp while the model is not able to simulate the high peaks that occur in this karst dominated area. The left–right shifting data shown at high elevations for areas outside the Tatiara PWA are those located in the Naracoorte ranges where observed data show large rises and then stable–declining trends in response to landuse changes not simulated by the model (e.g. BMA9-11, see Appendix A found in Volume 2 of this report).

The spatial distribution of the mean residuals for the transient model is shown in Figure 4.5. The simulated groundwater levels are too high in the eastern part of the Stirling GMA too low in the southern section of Willalooka GMA. It is possible that the high groundwater levels in the Stirling GMA are caused by an overestimation of recharge from approximately 2010–15 in some wells, while an underestimation of groundwater extraction is less likely since metered data is applied during this period. However, there are some hydrographs which are consistently overestimated (while matching the trends well) which could be explained by recharge that is consistently too high or too much thinning of the modelled aquifer from east to west in this area. This thinning of the Murray Group limestone aquifer contributes to the steep hydraulic gradient observed in what has been referred to as the transition zone by previous authors (i.e. Stadter and Love, 1989; Wood, 2011). If the modelled aquifer was thicker in western part of the Stirling GMA, the groundwater could be transmitted more rapidly for the same K value, and thus lower the simulated groundwater levels that are too high in the current models. This suggests that the structural uncertainty of the layer 2 bottom elevation surface in this location (i.e. the bottom of the unconfined aquifer interpolated from point data) warrants further investigation. It is important to note that this area of higher residuals is bounded in the east and west with hydrographs with low residuals, and so any structural alteration would also impact other parts of the model. Alternatively, the recharge in this area could be consistently overestimated leading to higher groundwater levels. However the recharge rates applied in the model are not considered excessive compared to field based estimates in the same area (e.g. Wohling et al., 2006), being scaled through calibration to average approximately 23, 35 and 375 mm/y for grazing, dryland cropping and flood irrigation landuses respectively. It was considered unrealistic to increase the hydraulic conductivity values beyond the upper bounds shown in Table 4.2.

The underestimated groundwater levels in the south of the Willalooka GMA are thought to be due to an underestimation of recharge in this area. This is likely to have been caused by the attribution of the small sections of the southern-most climate zones being replaced by drier zones from the north (see Morgan et al., 2017 for more detail). Groundwater levels are also too low in the northwest of the Padthaway PWA and in the far southeast of the model domain, which is also likely to be caused by an underestimation of recharge in this southern part of the model domain while also not attempting to simulate the transience of recharge rates due to land clearance in this area (i.e. landuse is constant in the recharge model, see Morgan et al., 2017 for more detail). Early versions of the model applied the original climate zones in this southern-most area which resulted in large recharge contrasts compared to the adjacent climate zones to the north and groundwater elevations that were much too high. Continuing with these larger recharge values in this area would have required much higher hydraulic conductivity values to be assigned to the MGL which were considered unreasonably high.

Overall the transient calibration is considered to be good with respect to residuals, while hydrograph fits are discussed in the next section and an assessment of the confidence that can be placed in the model results are discussed in the next chapter.

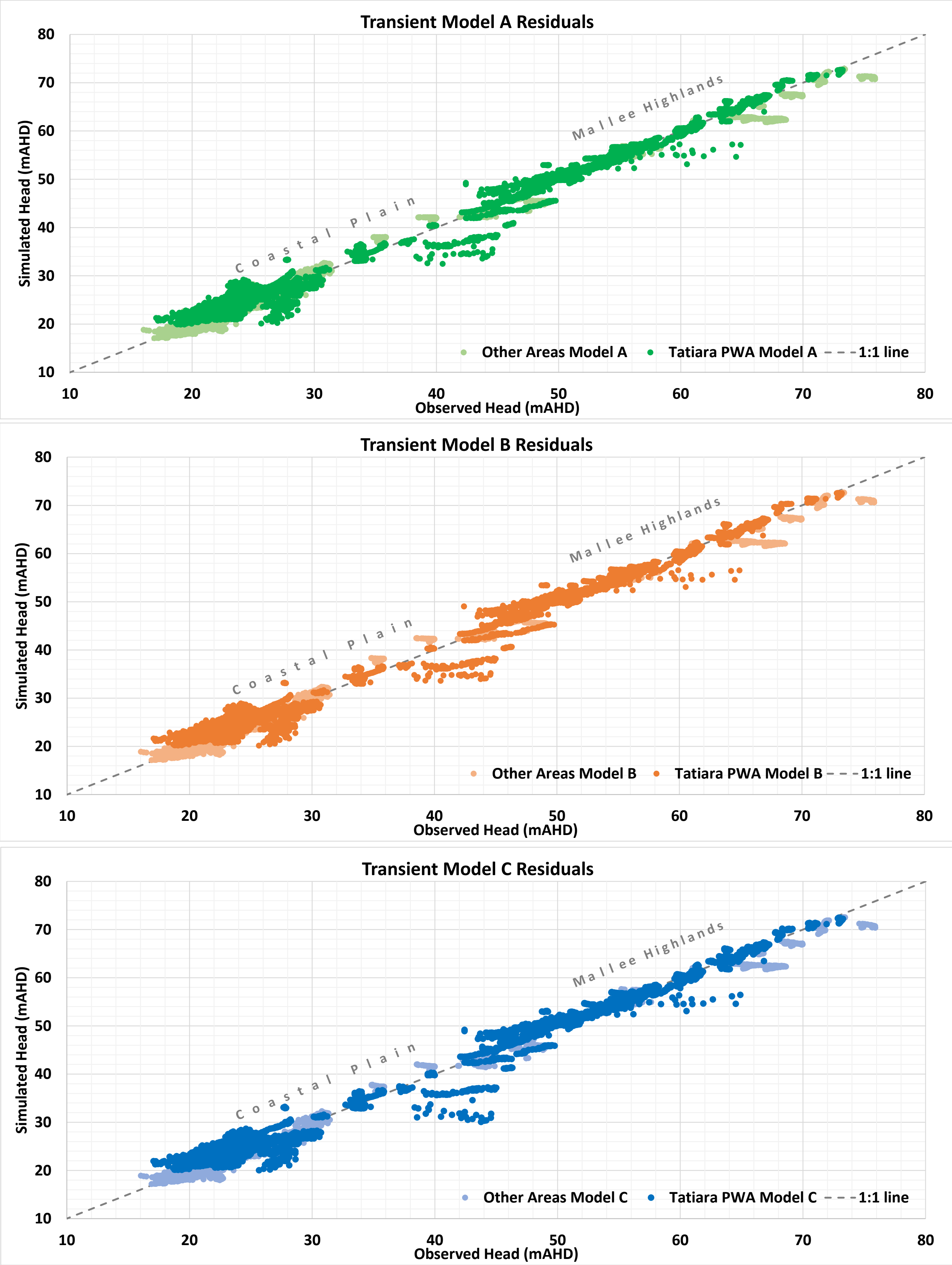

Figure 4.4. Transient state scatter of observed vs simulated heads within the Tatiara PWA and other model areas

Table 4.2 Transient initial, PEST and adopted values

	Zone or stress period	Lower bound	Upper bound	Initial value			PEST value			Adopted value		
				A	*B*	*C*	*A*	*B*	*C*	*A*	*B*	*C*
Hydraulic conductivity (m/d)	1	1	1000	951	900	900	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**
	2	1	300	200	200	200	**300**	**300**	**300**	**300**	**300**	**300**
	3	1	1000	42	227	57	201	411	393	201	411	393
	4	1	300	29	53	50	35	27	43	35	27	43
	5	1	300	80	200	124	291	297	**300**	291	297	**300**
	6	1	200	42	35	50	14	13	18	14	13	18
	7	1	200	85	134	127	143	177	**200**	143	177	**200**
	8	1	200	42	58	56	25	29	34	25	29	34
	9	1	300	30	41	38	12	16	19	12	16	19
	11	1	200	26	37	33	15	21	21	15	21	21
	12	1	200	48	82	60	62	57	91	62	57	91
	13	1	200	154	150	150	160	144	168	160	144	168
	14	1	300	38	70	73	47	62	29	47	62	29
	15	1	1000	370	900	378	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**
	16	1	200	25	24	21	5	3	19	5	3	19
	17	1	200	57	91	70	34	43	44	34	43	44
	18	1	200	12	17	16	15	14	20	15	14	20
Specific yield	1	0.05	0.25	0.15	0.15	0.15	**0.05**	**0.05**	0.05	0.15	0.15	0.15
	2	0.05	0.25	0.15	0.15	0.15	**0.05**	0.06	**0.05**	0.15	0.15	0.15
	3	0.05	0.25	0.15	0.15	0.15	**0.25**	**0.25**	**0.25**	0.20	0.20	0.20
	4	0.05	0.25	0.15	0.15	0.15	**0.25**	**0.25**	**0.25**	0.20	0.20	0.20
	5	0.05	0.25	0.15	0.15	0.15	**0.05**	**0.05**	**0.05**	0.10	0.10	0.10
	6	0.05	0.25	0.15	0.15	0.15	0.12	**0.05**	**0.05**	0.12	0.10	0.10
	7	0.05	0.25	0.15	0.15	0.15	0.10	0.11	**0.05**	0.10	0.12	0.10
	8	0.05	0.25	0.15	0.15	0.15	**0.25**	**0.25**	**0.25**	0.20	0.20	0.20
	9	0.05	0.25	0.15	0.15	0.15	**0.05**	**0.05**	**0.05**	0.10	0.10	0.10
	11	0.05	0.25	0.15	0.15	0.15	**0.25**	0.11	**0.05**	0.20	0.20	0.20
	12	0.05	0.25	0.15	0.15	0.15	**0.05**	**0.05**	**0.05**	0.20	0.20	0.20
	13	0.05	0.25	0.15	0.15	0.15	**0.05**	**0.05**	**0.05**	0.10	0.10	0.10
	14	0.05	0.25	0.15	0.15	0.15	**0.25**	**0.25**	**0.25**	0.20	0.20	0.20
	15	0.05	0.25	0.15	0.15	0.15	0.11	0.21	0.10	0.15	0.15	0.15
	16	0.05	0.25	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	17	0.05	0.25	0.15	0.15	0.15	**0.25**	**0.25**	**0.25**	0.20	0.20	0.20
	18	0.05	0.25	0.15	0.15	0.15	**0.25**	0.19	**0.25**	0.20	0.19	0.20
Recharge multiplier	1	0.5	1.5	0.96	1.30	1.27	1.01	1.14	1.28	1.01	1.14	1.28
	2	0.5	1.5	1.00	1.00	1.00	**1.50**	0.62	**0.50**	**1.50**	0.62	**0.50**
	3	0.5	1.5	1.00	1.00	1.00	**0.50**	0.92	0.69	**0.50**	0.92	0.69
	4	0.5	1.5	1.00	1.00	1.00	**1.50**	0.74	**0.50**	**1.50**	0.74	**0.50**

Zone or stress period	Lower bound	Upper bound	Initial value			PEST value			Adopted value		
			A	*B*	*C*	*A*	*B*	*C*	*A*	*B*	*C*
5	0.5	1.5	1.00	1.00	1.00	**1.50**	1.21	**1.50**	**1.50**	1.21	**1.50**
6	0.5	1.5	1.00	1.00	1.00	**1.50**	1.00	0.56	**1.50**	1.00	0.56
7	0.5	1.5	1.00	1.00	1.00	**0.50**	1.13	**1.50**	**0.50**	1.13	**1.50**
8	0.5	1.5	1.00	1.00	1.00	**1.50**	0.83	**0.50**	**1.50**	0.83	**0.50**
9	0.5	1.5	1.00	1.00	1.00	**0.50**	1.17	**1.50**	**0.50**	1.17	**1.50**
10	0.5	1.5	1.00	1.00	1.00	**1.50**	0.97	**0.50**	**1.50**	0.97	**0.50**
11	0.5	1.5	1.00	1.00	1.00	**1.50**	**1.50**	**1.50**	**1.50**	**1.50**	**1.50**
12	0.5	1.5	1.00	1.00	1.00	1.14	0.92	0.55	1.14	0.92	0.55
13	0.5	1.5	1.00	1.00	1.00	**0.50**	0.78	**0.50**	**0.50**	0.78	**0.50**
14	0.5	1.5	1.00	1.00	1.00	**0.50**	0.91	1.43	**0.50**	0.91	1.43
15	0.5	1.5	1.00	1.00	1.00	**1.50**	1.21	0.94	**1.50**	1.21	0.94
16	0.5	1.5	1.00	1.00	1.00	**1.50**	1.38	**1.50**	**1.50**	1.38	**1.50**
17	0.5	1.5	1.00	1.00	1.00	**0.50**	0.89	**0.50**	**0.50**	0.89	**0.50**
18	0.5	1.5	1.00	1.00	1.00	**1.50**	1.06	1.28	**1.50**	1.06	1.28
19	0.5	1.5	1.00	1.00	1.00	**1.50**	1.02	1.46	**1.50**	1.02	1.46
20	0.5	1.5	1.00	1.00	1.00	**0.50**	0.78	**0.50**	**0.50**	0.78	**0.50**
21	0.5	1.5	1.00	1.00	1.00	**0.50**	0.66	**0.50**	**0.50**	0.66	**0.50**
22	0.5	1.5	1.00	1.00	1.00	**1.50**	0.94	1.43	**1.50**	0.94	1.43
23	0.5	1.5	1.00	1.00	1.00	**0.50**	0.98	0.82	**0.50**	0.98	0.82
24	0.5	1.5	1.00	1.00	1.00	**1.50**	1.03	1.00	**1.50**	1.03	1.00
25	0.5	1.5	1.00	1.00	1.00	**1.50**	1.17	1.02	**1.50**	1.17	1.02
26	0.5	1.5	1.00	1.00	1.00	**0.50**	1.18	**1.50**	**0.50**	1.18	**1.50**
27	0.5	1.5	1.00	1.00	1.00	**0.50**	0.58	**0.50**	**0.50**	0.58	**0.50**
28	0.5	1.5	1.00	1.00	1.00	**0.50**	1.14	**1.50**	**0.50**	1.14	**1.50**
29	0.5	1.5	1.00	1.00	1.00	**0.50**	0.53	**0.50**	**0.50**	0.53	**0.50**
30	0.5	1.5	1.00	1.00	1.00	**0.50**	0.87	**1.50**	**0.50**	0.87	**1.50**
31	0.5	1.5	1.00	1.00	1.00	**0.50**	0.81	**0.50**	**0.50**	0.81	**0.50**
32	0.5	1.5	1.00	1.00	1.00	1.38	0.91	**1.50**	1.38	0.91	**1.50**
33	0.5	1.5	1.00	1.00	1.00	**0.50**	0.79	**0.50**	**0.50**	0.79	**0.50**
34	0.5	1.5	1.00	1.00	1.00	**0.50**	0.78	**0.50**	**0.50**	0.78	**0.50**
35	0.5	1.5	1.00	1.00	1.00	**0.50**	1.00	**1.50**	**0.50**	1.00	**1.50**
36	0.5	1.5	1.00	1.00	1.00	**0.50**	0.90	1.35	**0.50**	0.90	1.35
37	0.5	1.5	1.00	1.00	1.00	**0.50**	0.66	**0.50**	**0.50**	0.66	**0.50**
38	0.5	1.5	1.00	1.00	1.00	**0.50**	0.98	**1.50**	**0.50**	0.98	**1.50**
39	0.5	1.5	1.00	1.00	1.00	**0.50**	0.81	**0.50**	**0.50**	0.81	**0.50**
40	0.5	1.5	1.00	1.00	1.00	**0.50**	0.68	**0.50**	**0.50**	0.68	**0.50**
41	0.5	1.5	1.00	1.00	1.00	**0.50**	0.77	**1.50**	**0.50**	0.77	**1.50**
42	0.5	1.5	1.00	1.00	1.00	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**
43	0.5	1.5	1.00	1.00	1.00	**0.50**	0.79	**1.50**	**0.50**	0.79	**1.50**
44	0.5	1.5	1.00	1.00	1.00	**0.50**	0.67	**0.50**	**0.50**	0.67	**0.50**

	Zone or stress period	Lower bound	Upper bound	Initial value			PEST value			Adopted value		
				A	*B*	*C*	*A*	*B*	*C*	*A*	*B*	*C*
	45	0.5	1.5	1.00	1.00	1.00	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**
	46	0.5	1.5	1.00	1.00	1.00	**0.50**	0.65	0.87	**0.50**	0.65	0.87
	47	0.5	1.5	1.00	1.00	1.00	**0.50**	0.60	**0.50**	**0.50**	0.60	**0.50**
	48	0.5	1.5	1.00	1.00	1.00	**0.50**	0.53	**0.50**	**0.50**	0.53	**0.50**
	49	0.5	1.5	1.00	1.00	1.00	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**
	50	0.5	1.5	1.00	1.00	1.00	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**
	51	0.5	1.5	1.00	1.00	1.00	**0.50**	0.59	**0.50**	**0.50**	0.59	**0.50**
	52	0.5	1.5	1.00	1.00	1.00	**0.50**	0.69	**0.50**	**0.50**	0.69	**0.50**
	53	0.5	1.5	1.00	1.00	1.00	**0.50**	0.57	**0.50**	**0.50**	0.57	**0.50**
	54	0.5	1.5	1.00	1.00	1.00	**0.50**	0.64	**0.50**	**0.50**	0.64	**0.50**
	55	0.5	1.5	1.00	1.00	1.00	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**
	56	0.5	1.5	1.00	1.00	1.00	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**
	57	0.5	1.5	1.00	1.00	1.00	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**
	58	0.5	1.5	1.00	1.00	1.00	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**
	59	0.5	1.5	1.00	1.00	1.00	**0.50**	**0.50**	0.88	**0.50**	**0.50**	0.88
	60	0.5	1.5	1.00	1.00	1.00	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**
	61	0.5	1.5	1.00	1.00	1.00	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**
	62	0.5	1.5	1.00	1.00	1.00	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**

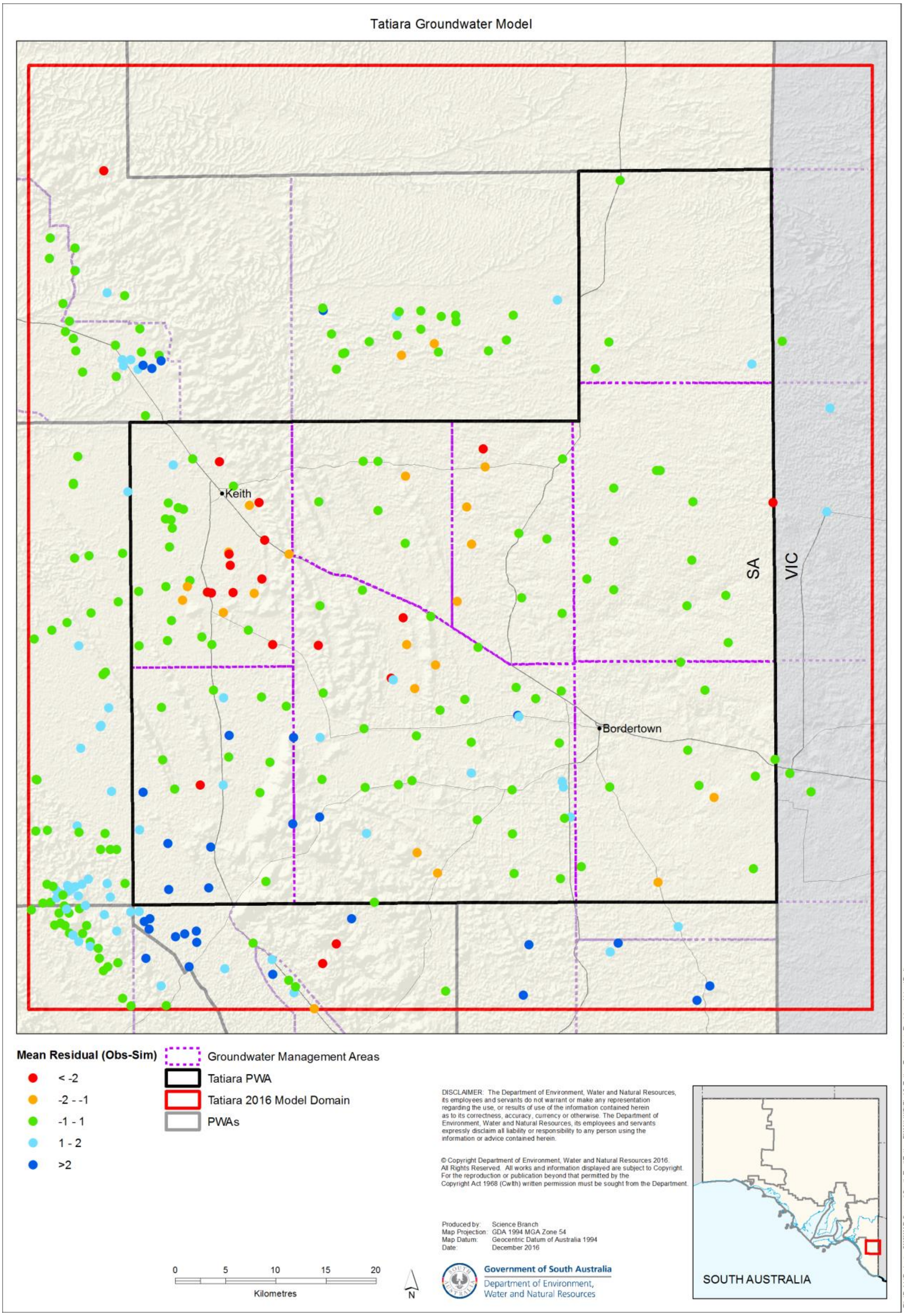

Figure 4.5. Transient model mean residuals, where residual equals the observed minus the simulated water level

4.3.1 Selected groundwater hydrographs of simulated and observed heads

Representative hydrographs from each GMA within the Tatiara PWA are shown in Figure 4.6, Figure 4.7 and Figure 4.8 while each hydrograph used in model calibration can be seen in Appendix A found in Volume 2 of this report.

The hydrographs shown in Figure 4.6 for the Cannawigara, Shaugh and Zone 8A GMAs show good agreement between the observed and simulated groundwater levels. There are subtle deviations, such as the offset of approximately 1 m for CAN12 or the over-estimated declining trend over the last 10 years in SEN4/15 and CAN14 but these are considered minor given the scale of the groundwater model. There do not appear to be any significant stresses on the groundwater resources in these GMAs as reflected by the very stable trends (with the exception of CAN14 where a small decline is seen from ~2000 onwards). Additionally, SHG4 shows greater variation than other observation wells in this area (located in the southwest of the Shaugh GMA), and is influenced by nearby extraction.

Figure 4.7 shows selected hydrographs for the Stirling, Willalooka and Wirrega GMAs. It is clear that there are larger changes in groundwater level in these GMAs with seasonal fluctuations of up to 2 m and declining trends from the mid-1990s onwards resulting in a lowering of the water table by up to 4 m in some areas. The model shows good agreement between the observed and simulated groundwater levels in terms of level and trends. However the declining trends are slightly under-predicted in Stirling over the last five to ten years of the calibration period. The rationalization of S_y values after the final PEST iteration and slight de-calibration of the model also contribute to the slight under-prediction of water levels during this period. Given the relative insensitivity of the model fit to S_y parameters it was considered reasonable to alter S_y values that hit the lower and upper bounds to more commonly accepted values (i.e. 0.05 to 0.1 and 0.25 to 0.2) as previously discussed. It is also possible that groundwater extraction has been over-estimated prior to metered data or alternatively, recharge may be over-estimated in the last 10 years in this area. The seasonal variation in model hydrographs is less than the variation seen in some observation wells (e.g. WLL20 and WLL107) while this variation is greater than that observed in other areas (e.g. STR116). These discrepancies are expected due to the uncertainty of the groundwater extraction distribution in the historical period. Nevertheless, these hydrographs are simulated very well overall in terms of general trend and groundwater level elevation (see Section 4.4 for discussion on model confidence).

A selection of hydrographs are also shown for North Pendleton and Tatiara GMAs as well as one from the Hundred of Laffer and one from Victoria just outside of the Tatiara PWA (Figure 4.8). The model shows very good agreement with the observed hydrographs for these areas with respect to both level, seasonal variability and trends. The slightly overestimated declining trend in TAT106 and 75635 is similar to the behavior noted previously in Cannawigara and Zone 8A. This is a result of the recharge being reduced across the entirety of the model domain in order to better match the water level declines in coastal plain. The current version of MODFLOW only allows a single recharge multiplier for each stress period and thus a tradeoff has been made in the calibration of the coastal plain (which requires less recharge) and the Mallee highlands (which requires more recharge) in the latter part of the calibration period. In reality, recharge in the Mallee highlands should be very stable and any seasonal or multi-year trend will be considerably damped by water movement through deep unsaturated zones. The declining trends observed closer to, or within, the coastal plain (e.g. TAT18 and PET14) reflect the declining storage in that area and to the west (see discussion of groundwater balances in the following section).

There are no significant differences between the three models in terms of their ability to fit the observed water level data. Subtle differences exist in some of the Mallee highland observation wells where the slight downward trends from the mid-1990s onwards are steeper with increasing scaling factors. These differences are discussed further below in terms of groundwater balances.

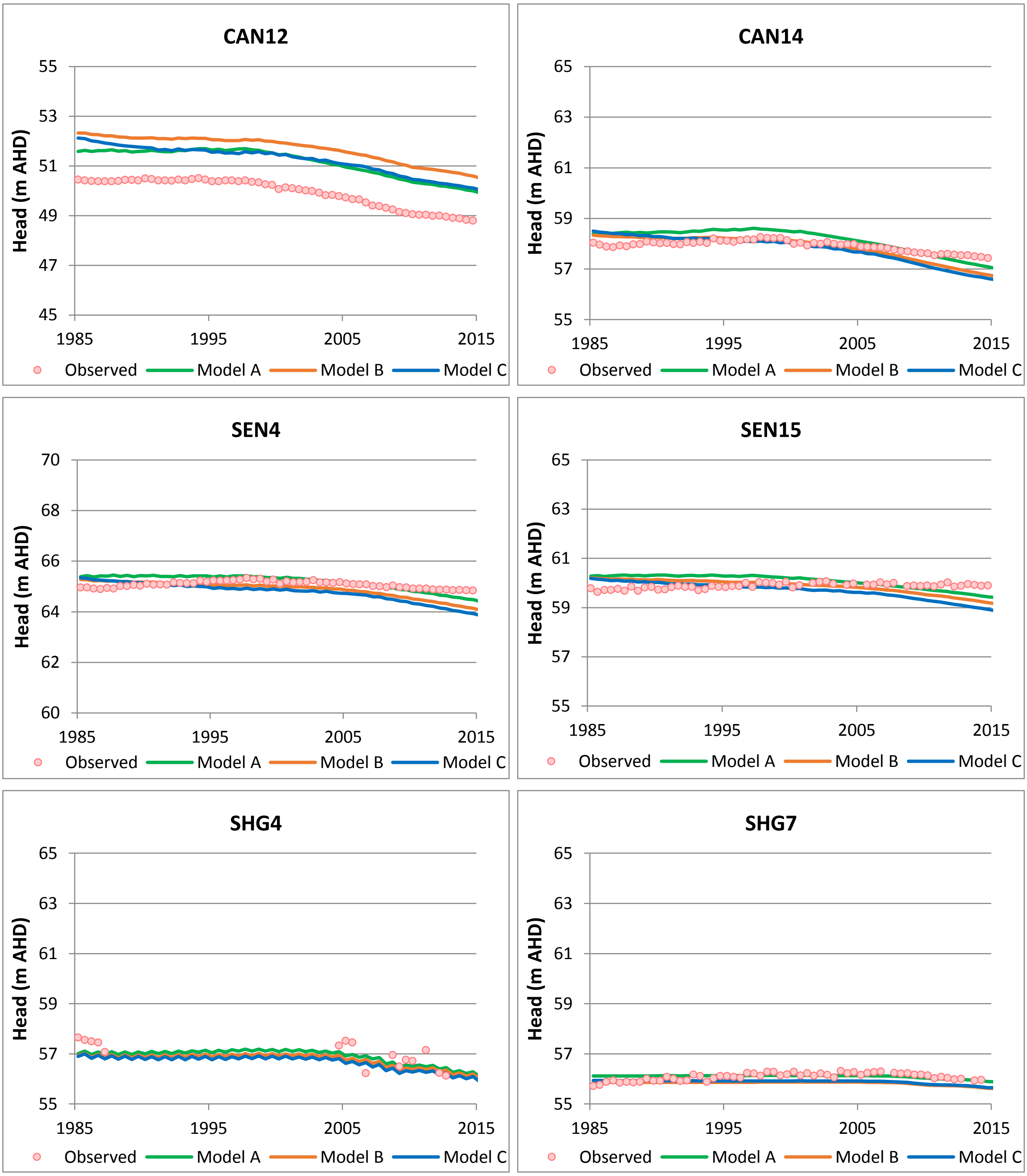

Figure 4.6. Groundwater hydrographs for Cannawigara, Shaugh and Zone 8A GMAs

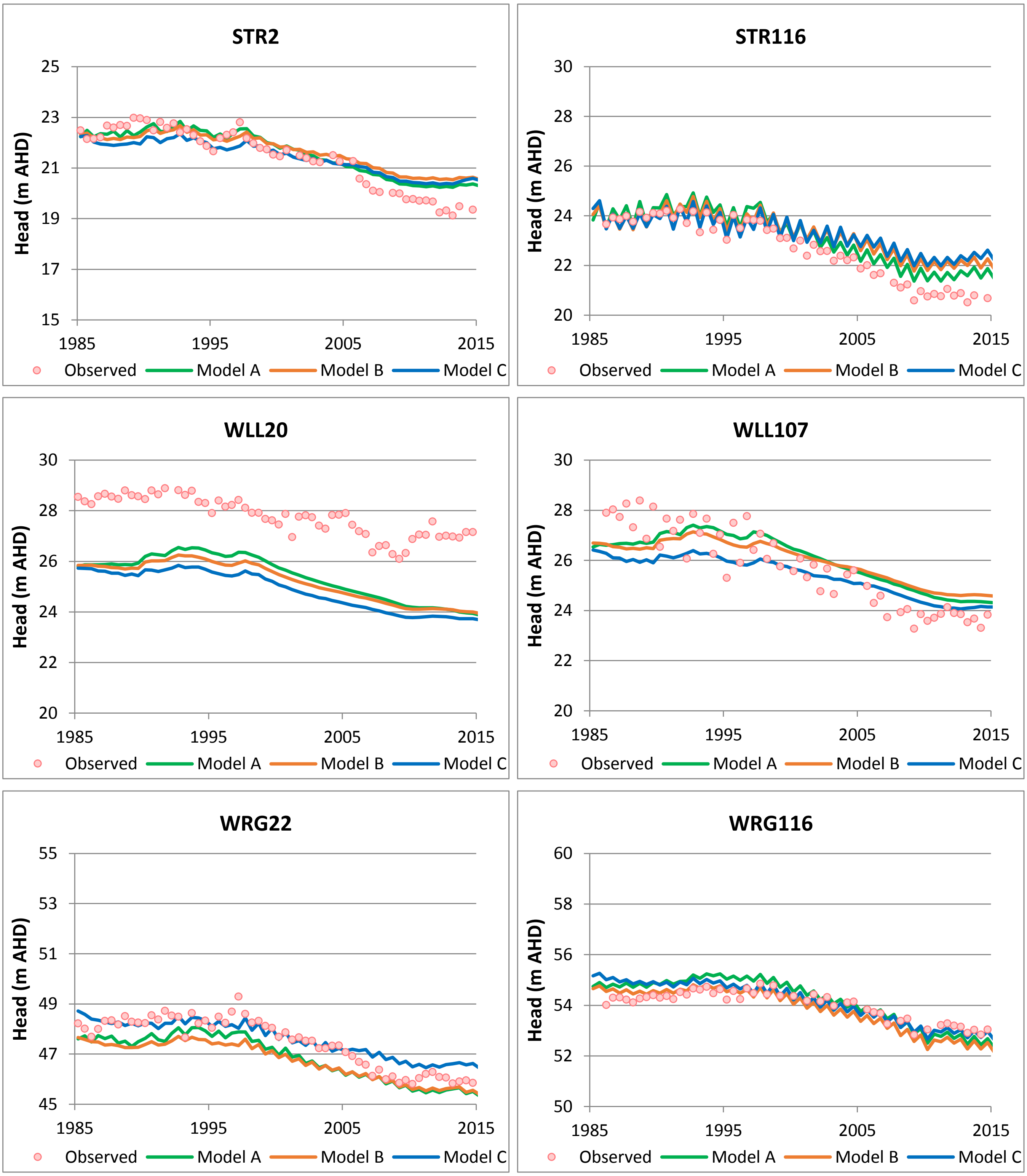

Figure 4.7. Groundwater hydrographs for Stirling, Willalooka and Wirrega GMAs

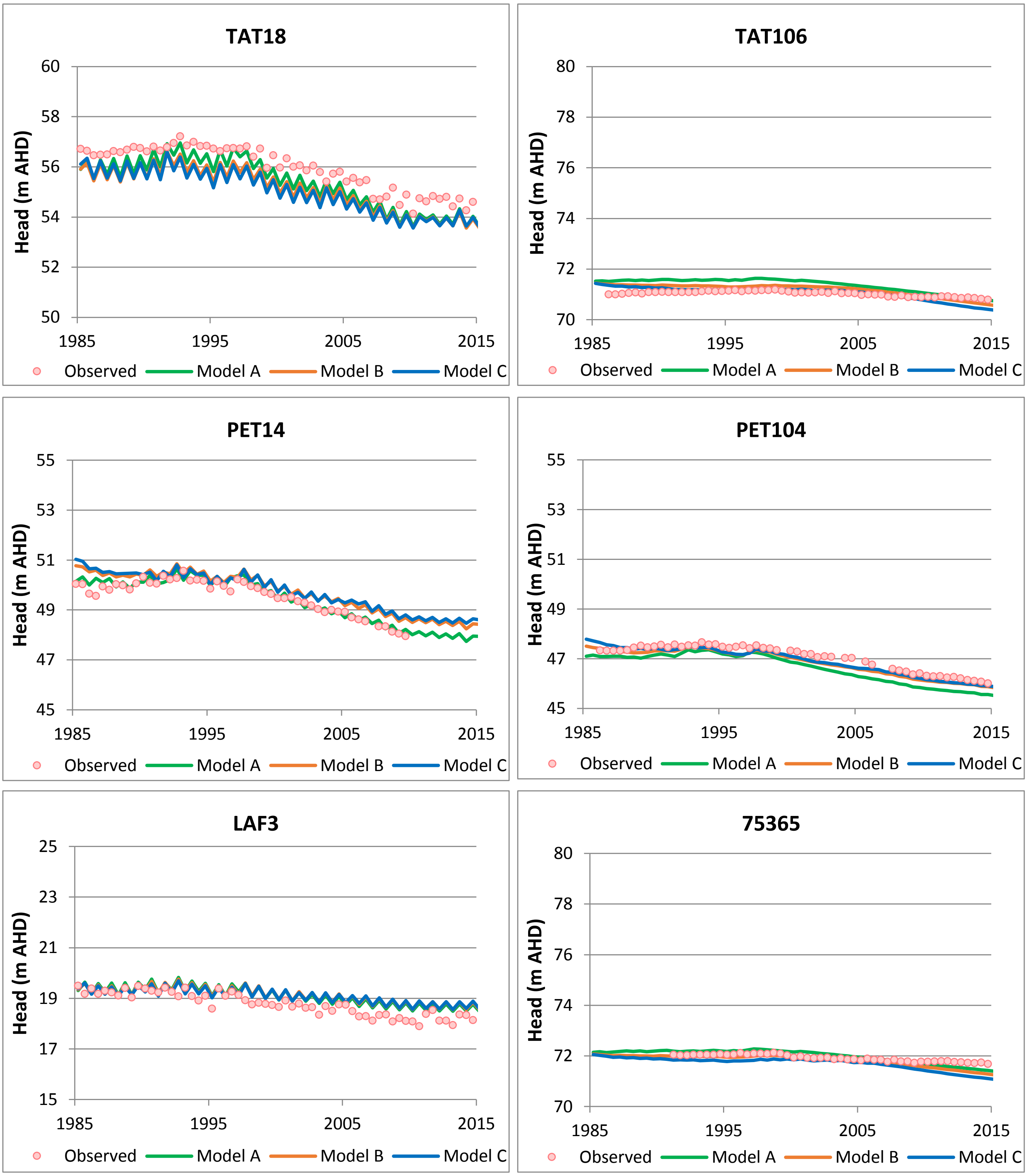

Figure 4.8. Groundwater hydrographs for Tatiara GMA, North Pendleton GMA, the Hundred of Laffer and Victoria

4.3.2 Tatiara PWA groundwater mass balance

The overall mass balance for the Tatiara PWA is shown in Figure 4.9. The major inputs are diffuse recharge (both rainfall and irrigation return), regional inflow from the east and point recharge at Poocher and Mundulla Swamps. The major outputs are groundwater extraction, regional outflow to the west and some groundwater ET, also in the west. It can be seen that over time there is a consistent reduction in net storage, with the exception of high recharge years (e.g. 1990, 1992 and 1997). This is consistent with the ongoing declining groundwater levels observed across the coastal plain GMAs, and is primarily caused by the reduction in diffuse recharge after the mid-1990s. Outflow to the west and groundwater ET also reduced over this time period due to the continued decrease in groundwater storage (i.e. as groundwater levels decline). Regional inflows are consistent from year to year suggesting that groundwater inflow to the region is not influenced significantly during the simulated period (1985–2015) by extraction stresses or changes in recharge, particularly in the east. Meanwhile point recharge though Poocher and Mundulla Swamps (dependent on creek flow generated typically by winter rainfall) are more variable and a relatively small component of the groundwater balance. The total groundwater extraction rates are relatively consistent over time and generally lower than the average total inputs to the system until the end of the 1990s. Within this earlier period there are some years where storage decreases considerably due to lower diffuse recharge (i.e. 1986, 1991 and 1995). After the late 1990s, there are consistent declines in groundwater storage and the Tatiara PWA on the whole is being depleted.

Average groundwater balance components are shown in Table 4.3 for each of the three calibrated models in addition to the average of the three models. These have been broken up into two periods of time, from 1985–99 and from 2000–15. For example, diffuse recharge averages 128 GL/y in the first period and is reduced to 63 GL/y in the later period. This suggests that the primary cause of declining groundwater levels is reduced recharge rather than groundwater extraction which has been relatively constant over the past 30 years. However, lower rates of groundwater extraction (i.e. less than the average 90 GL/y) would certainly cause the reduction in storage to be lessened by approximately an equivalent amount, as demonstrated in the last five years (i.e. 2010–15 in Figure 4.9).

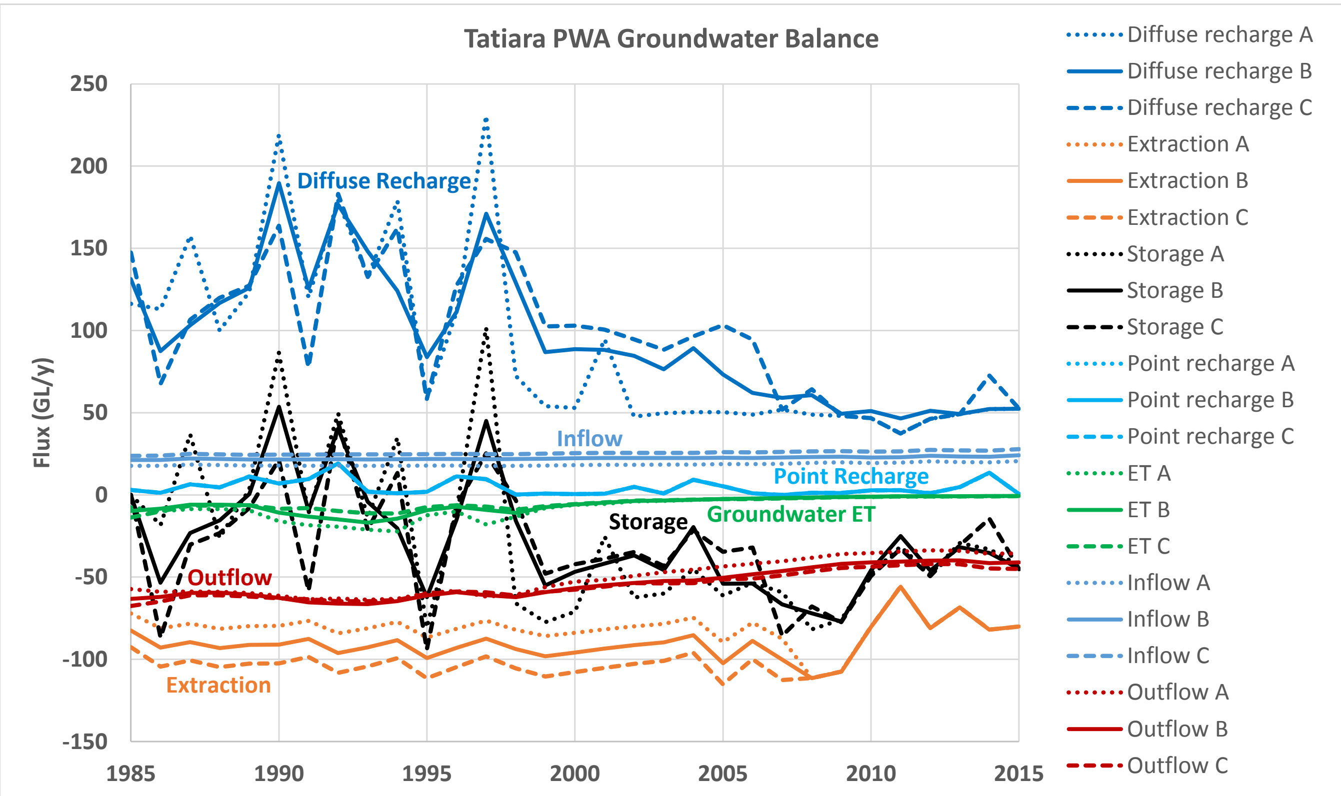

Figure 4.9. Groundwater mass balance for the Tatiara PWA showing results of all calibrated models (A, B and C denote groundwater models with coastal plain scaling factors of 1.4, 1.6 and 1.8 applied to extraction estimates based on crop requirement prior to metered data)

4.3.3 Coastal plain groundwater mass balance

The coastal plain groundwater balance is very similar to the Tatiara PWA groundwater balance as the largest recharge and discharge processes occur in this area (Figure 4.10 and Table 4.3). Diffuse recharge is large but highly variable from 1986–2000 (average of 94 GL/y), before becoming lower on average (43 GL/y) in the latter 15 years. Groundwater inflow from the east is a consistent source of groundwater to this area (ranging from 29–49 GL/y), which increases over time as storage is reduced from the late-1990s to 2015. Groundwater extraction is the largest output, averaging 72, 79 and 87 GL/y for Models A, B and C respectively with a reduction of 9 GL/y between the first and last 15-year average periods. Regional outflow to the west is seen to reduce between the averaging periods of 1986–2000 and 2001–15 from 51 to 34 GL/y. This outflow and groundwater ET both decrease over time as water levels on the coastal plain decline. Point recharge through Mundulla and Poocher Swamps are dependent on winter rainfall and contribute a relatively small input to the groundwater system (averaging 5 GL/y). The patterns of groundwater storage reduction and groundwater extraction mirror each other from the mid-2000s onwards. This demonstrates that when diffuse recharge is low, the magnitude of the depletion of the groundwater system is directly influenced by groundwater extraction. For example, the low extraction year in 2011 results in only a very small reduction in groundwater storage while a similarly low extraction year in 2013 shows a small increase in groundwater storage.

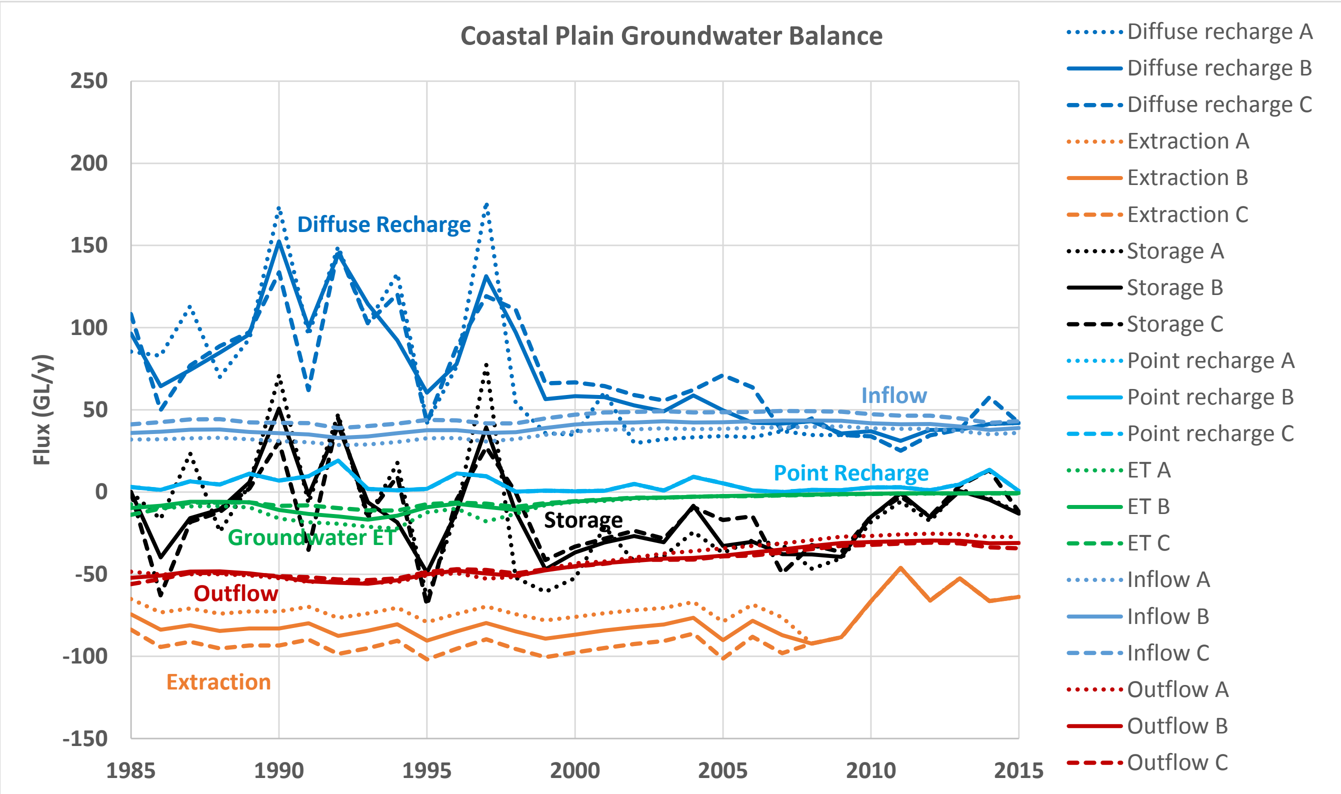

Figure 4.10. Groundwater mass balance for the coastal plain within the Tatiara PWA showing results of all calibrated models (A, B and C denote groundwater models with coastal plain scaling factors of 1.4, 1.6 and 1.8 applied to extraction estimates based on crop requirement prior to metered data)

4.3.4 Mallee highland groundwater mass balance

The groundwater mass balance for the Mallee highland is shown in Figure 4.11. Relative to the coastal plain the inputs and outputs are relatively small and show less variation. This is consistent with the mostly stable groundwater levels within the Mallee highlands, particularly in the east towards Victoria (e.g. TAT20, SEN5, and SHG2). Diffuse recharge averages reduce from 31 to 19 GL/y between the first and last 15 years of the calibration period with an overall average of 25 GL/y. Inflow from the west is relatively constant (20 GL/y) with only small increases from the start to end of the calibration period of 2, 3 and 5 GL/y for Models A, B and C respectively. Outflow towards the coastal plain is the major output which averages 49 GL/y and increases on average by 5 GL/y between the periods of 1986–2000 and 2001–15. These throughflow fluxes are seen to vary proportionally with different extraction rates on the coastal plain between the three models. There is only a small change in storage for the 1986–2000 period (5 GL/y), while the models show larger reductions in storage over the period from 2001–15 (26 GL/y). This is a result of the reduction in recharge and increase in outflow between these two periods. The reduction in recharge is required by the model in order to better match the declining water level trends in the coastal plain. This reduction clearly influences the groundwater balance of the Mallee highlands, where a reduction to recharge on this time scale would not be expected in reality (see previous discussion in Section 4.3.1 as related to observed water levels). The application of reduced recharge on the Mallee highlands (i.e. applied to the whole model) is an unfortunate limitation of MODFLOW. Spatially variable multipliers could be applied in a future revision of the model using elaborate coding to be incorporated into calibration using PEST or subjective manual adjustments applied to the transient recharge dataset outside of MODFLOW itself. Thus the decline in recharge to the Mallee highlands is an artefact of the reduction required on the coastal plain, and the impact on the groundwater balance and hydrographs should be noted.

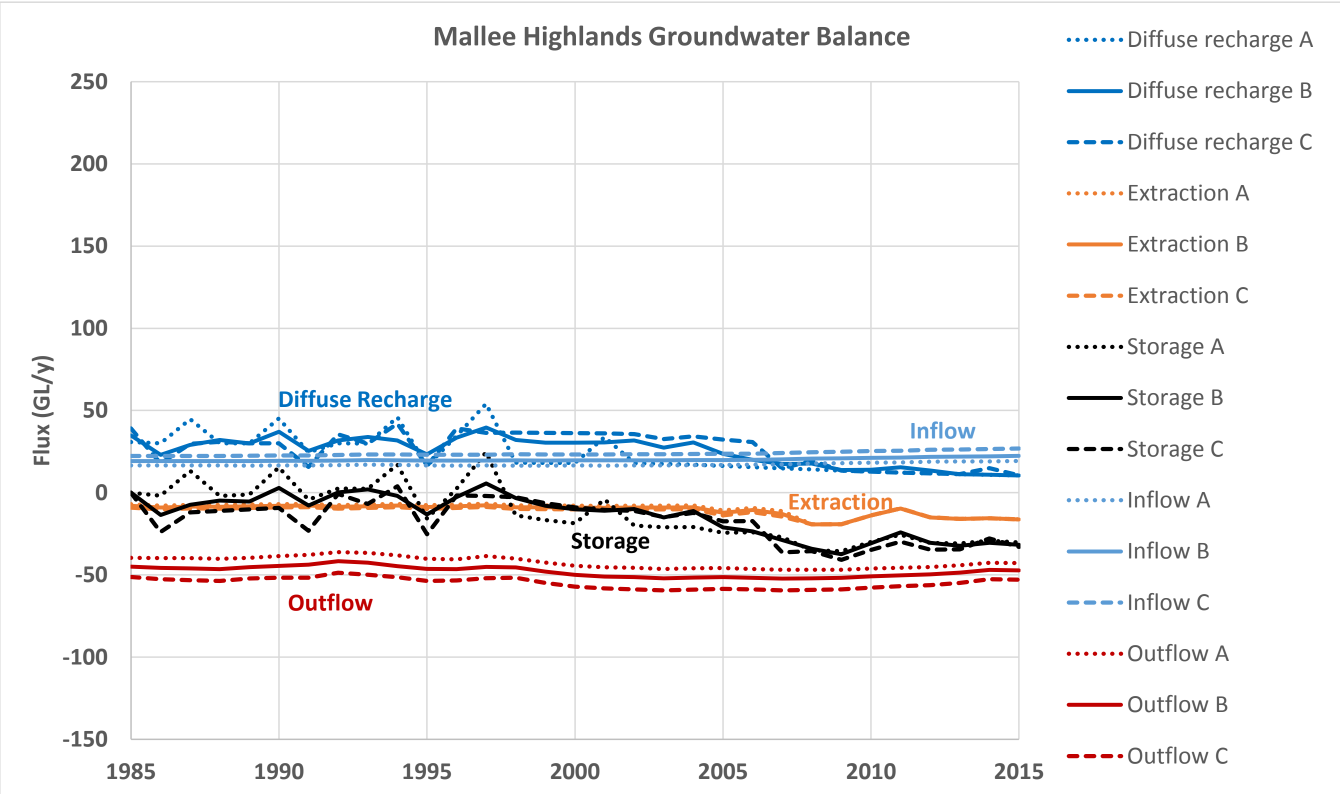

Figure 4.11. Groundwater mass balance for the Mallee highlands within the Tatiara PWA showing results of all calibrated models (A, B and C denote groundwater models with coastal plain scaling factors of 1.4, 1.6 and 1.8 applied to extraction estimates based on crop requirement prior to metered data)

4.3.5 Groundwater Management Area groundwater mass balances

The groundwater mass balances for individual GMAs are briefly discussed and shown as figures and tables in Appendix B of Volume 2 of this report. Generally, the findings discussed above for the coastal plain and Mallee highland apply similarly to GMAs that are within these hydrogeological zones. The Wirrega GMA which has large portions in each zone, has been divided to illustrate the differences in the behavior of the aquifer (i.e. larger more variable fluxes on the coastal plain and more stable conditions in the Mallee highland portion).

Table 4.3 Average groundwater balances (GL/y) for the Tatiara PWA including the division between coastal plain and Mallee highlands

									Tatiara PWA												
Date	*Diffuse recharge*			*Extraction*			*Storage*			*Point recharge*			*Groundwater ET*			*Inflow*			*Outflow*		
Steady State (A, B, C)	116	131	147	-72	-82	-93	0	0	0	3	3	3	-8	-10	-14	18	21	24	-57	-63	-68
Steady State (mean)		**132**			**-82**			**0**			**3**			**-10**			**21**			**-63**	
1986-2000 (A, B, C)	127	125	122	-81	-93	-104	-4	-12	-21	6	6	6	-13	-10	-8	18	22	25	-60	-62	-62
1986-2000 (mean)		**125**			**-93**			**-12**			**6**			**-10**			**21**			**-61**	
2001-2015 (A, B, C)	52	63	70	-82	-88	-93	-51	-46	-44	3	3	3	-2	-2	-2	19	23	26	-40	-46	-48
2001-2015 (mean)		**61**			**-88**			**-47**			**3**			**-2**			**23**			**-45**	
1986-2015 (A, B, C)	89	94	96	-82	-90	-99	-27	-29	-33	5	5	5	-8	-6	-5	19	22	26	-50	-54	-55
1986-2015 (mean)		**93**			**-90**			**-30**			**5**			**-6**			**22**			**-53**	
									Coastal Plain												
Date	*Diffuse recharge*			*Extraction*			*Storage*			*Point recharge*			*Groundwater ET*			*Inflow*			*Outflow*		
Steady State (A, B, C)	85	96	108	-65	-74	-84	0	0	0	3	3	3	-8	-10	-14	32	36	41	-49	-52	-56
Steady State (mean)		**97**			**-74**			**0**			**3**			**-10**			**36**			**-52**	
1986-2000 (A, B, C)	96	94	91	-74	-84	-95	-4	-8	-12	6	6	6	-13	-10	-8	32	37	43	-51	-51	-50
1986-2000 (mean)		**94**			**-84**			**-8**			**6**			**-10**			**37**			**-51**	
2001-2015 (A, B, C)	36	44	48	-70	-75	-80	-25	-22	-18	3	3	3	-2	-2	-2	38	42	47	-31	-35	-36
2001-2015 (mean)		**43**			**-75**			**-21**			**3**			**-2**			**42**			**-34**	
1986-2015 (A, B, C)	66	69	70	-72	-79	-87	-14	-15	-15	5	5	5	-8	-6	-5	35	39	45	-41	-43	-43
1986-2015 (mean)		**68**			**-79**			**-15**			**5**			**-6**			**40**			**-42**	
									Mallee Highlands												
Date	*Diffuse recharge*			*Extraction*			*Storage*			*Point recharge*			*Groundwater ET*			*Inflow*			*Outflow*		
Steady State (A, B, C)	31	35	39	-7	-8	-9	0	0	0	0	0	0	0	0	0	17	19	22	-40	-45	-51
Steady State (mean)		**35**			**-8**			**0**			**0**			**0**			**19**			**-45**	
1986-2000 (A, B, C)	31	31	31	-7	-8	-9	0	-5	-9	0	0	0	0	0	0	17	19	23	-40	-46	-53
1986-2000 (mean)		**31**			**-8**			**-5**			**0**			**0**			**20**			**-46**	
2001-2015 (A, B, C)	15	19	22	-13	-13	-14	-26	-25	-26	0	0	0	0	0	0	18	21	25	-46	-51	-57
2001-2015 (mean)		**19**			**-13**			**-26**			**0**			**0**			**21**			**-51**	
1986-2015 (A, B, C)	23	25	26	-10	-11	-12	-13	-15	-18	0	0	0	0	0	0	17	20	24	-43	-48	-55
1986-2015 (mean)		**25**			**-11**			**-15**			**0**			**0**			**20**			**-49**	

4.4 Model confidence

In order to assess the appropriate degree of confidence to be placed on model results and future projections, it is important to evaluate how well the model is able to simulate both the magnitude and trends of groundwater levels during the calibration period. These two components can be evaluated based on mean residuals and an assessment of the similarity between simulated and observed trends and variations. Using the groundwater level data and hydrographs presented in Appendix A (found in Volume 2 of this report), the mean residual for each observation well has been calculated and the trends of each hydrograph have been qualitatively assessed. These have each been categorized into three groups as shown in Table 4.4 within combinations resulting in 'High', 'Medium ', 'Low' or 'N/A' confidence rankings.

Table 4.4. Confidence level classification matrix for all unconfined aquifer observation wells

Residual (m)	Residual class	Ability to simulate trends and dynamics			
		Poor	*Reasonable*	*Good*	*N/A*
< +/- 1	*Good*	Medium	High	High	N/A
+/- 1 to +/- 2	*Reasonable*	Low	Medium	Medium	N/A
> +/- 2	*Poor*	Low	Low	Low	N/A

4.4.1 Groundwater level mean residuals

Due to the six-monthly stress periods of the model we should not necessarily expect the model to accurately simulate drawdown with pumping averaged over six months and observation wells located at a range of distances from pumping wells (additionally, some observation wells are also pumping wells and may contain some bias towards lower heads during summer). However, if there were multiple observations within a stress period these have been averaged so that the target observations are closer to what the model is simulating. This has the influence of reducing the seasonal variability of observations in some cases (particularly early in the calibration period where up to monthly observations were recorded but not others where only six-monthly data is available), and so there is uncertainty in the representativeness of observation targets. This uncertainty has been translated into three residual classification rankings of 'Good', 'Reasonable' and 'Poor' residuals (Table 4.5).

A histogram of the frequency of residual ranges is shown in Figure 4.12 for all observations and summarised in Table 4.5 as averages for each observation well, while the spatial distribution is later shown in Figure 4.13. The residual is calculated by subtracting the simulated head from the observed head and so a negative residual means the model heads are too high while a positive residual means the model heads are too low. The water levels are more frequently overestimated within Tatiara PWA while they are more frequently underestimated in areas outside the PWA. This slight underestimation outside of the PWA mostly occurs in the southwest of the model and may be in part, due to the lowering of recharge rates in the southern section of the model (see Section 3.5.3). The slight overestimates of water levels within the Tatiara PWA may be due to underestimation of total extraction in combination with an overestimation of recharge or alternatively, simply due to the inability of the model to accurately simulate groundwater levels and trends in all areas of the model domain due to heterogeneity of the aquifer properties and/or structure.

Overall, 59, 56 and 55% of observations for Models A, B and C respectively, fall within +/- 1 m and are considered 'Good' in terms of residuals. An additional 26, 27 and 28% of observations for Models A, B and C respectively are within +/- 2 m and considered 'Reasonable' in terms of residuals. The remaining 15, 17 and 18% of residuals are considered 'Poor' for Models A, B and C. These poorly fitted observation wells are located in areas where there is uncertainty in the hydrogeological structure of the aquifers (i.e. thin or discontinuous) and the model is not able to simulate the water level accurately (see Figure 4.13). Despite these relatively high residuals, the behavior of the simulated groundwater levels is generally good for these wells (see discussion below).

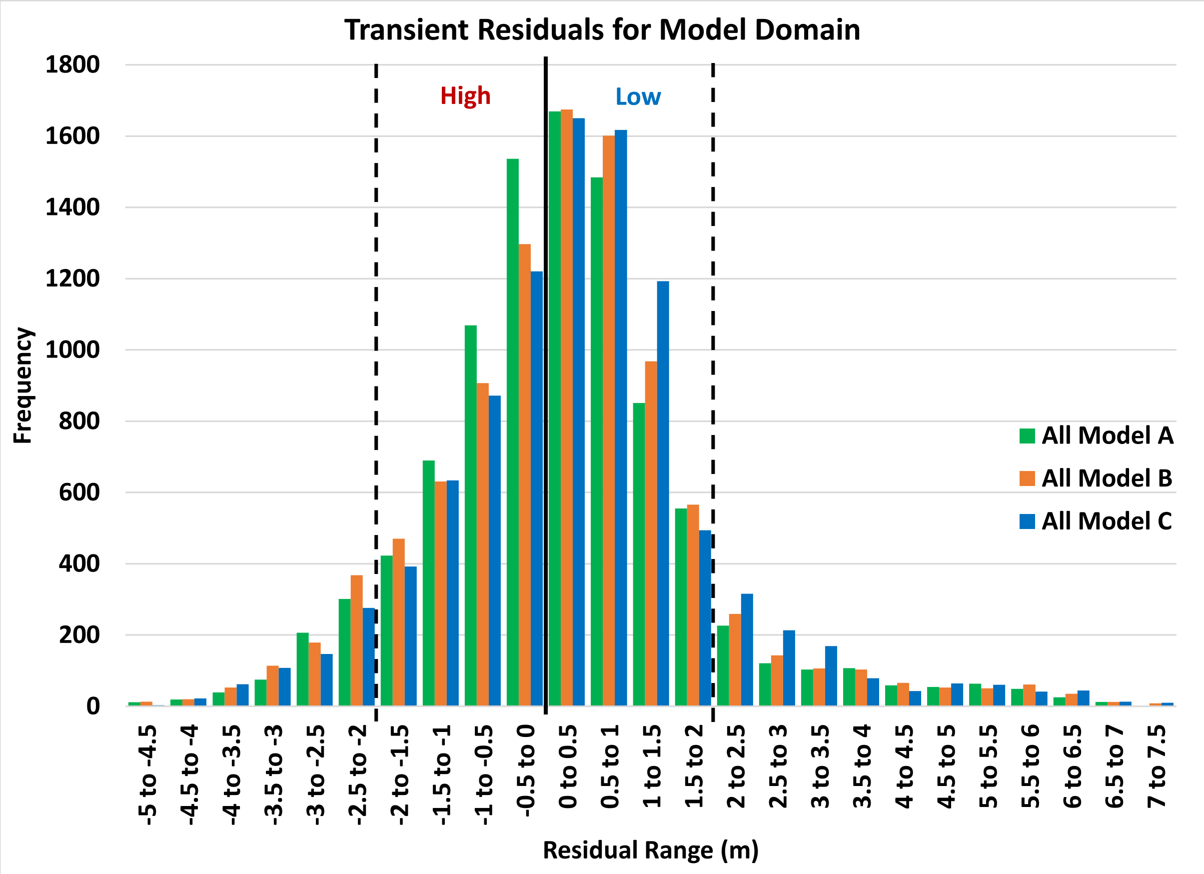

Figure 4.12. Histogram of residual ranges for all observation wells within the Tatiara PWA and other model areas

The mean residual classification for each GMA is shown in Table 4.5 with the average of all three models used to define the classification. The majority of GMAs are dominated by ‘Good’ and ‘Reasonable’ mean residuals as is the Tatiara PWA as a whole. The GMAs on the coastal plain (i.e. Stirling, Willalooka and Wirrega) contain the most variation in mean residual classification and this is likely due to uncertainty in the hydrogeological structure of the unconfined aquifer (i.e. thin or discontinuous features, unclear lithology) and the influence this may have on recharge, groundwater extraction and groundwater flow. The model simulates the vertical heterogeneity in 2 layers and horizontal heterogeneity in 18 zones which does not fully represent the true vertical and horizontal heterogeneity that exists in the aquifers. This results in a number of ‘Poor’ residuals which are considered to be acceptable within a regional model. Representing the hydraulic parameters of the aquifer using pilot points instead of zones may help reduce the number of ‘Poor’ residuals. This approach could be tested in future revisions of the model.

Table 4.5. Residual classification

Area	Residual classification		
	Good	*Reasonable*	*Poor*
Stirling GMA	21	8	11
Willalooka GMA	10	3	8
Wirrega GMA	25	13	7
North Pendleton GMA	5	1	0
Cannawigara GMA	5	4	1
Shaugh GMA	3	1	0
Zone 8A GMA	11	0	1

Area	Residual classification		
	Good	*Reasonable*	*Poor*
Tatiara GMA	9	2	0
Tatiara PWA	**89**	**32**	**28**
Other Areas	90	50	23
All Models	179	82	51

4.4.2 Groundwater level trends and variability

The trend and variability classification was determined for 209 observation wells over the calibration period with adequately long time series records. Because there were very few hydrographs where the behavior of simulated hydrographs differed between models, we have considered their behavior as a whole for classification purposes. The remaining 103 hydrographs were not assessed due to a lack of continuous data or clear trends and are counted as N/A in Table 4.6. The majority of observation wells in each GMA show either 'Good' or 'Reasonable' matches between simulated and observed groundwater behavior. There are only 3 observation wells having 'Poor' matches within the Tatiara PWA and these are found within the Wirrega GMA in locations where there is uncertainty about the structure of thin and/or discontinuous aquifer units. As previously discussed, the trends are also not well matched in some parts of the Naracoorte Ranges. The spatial distribution of these classifications can be seen in Figure 4.14.

Table 4.6. Trend and variability classification

Area	Trend and variability classification			
	Good	*Reasonable*	*Poor*	*N/A*
Stirling GMA	23	6	0	11
Willalooka GMA	8	10	0	3
Wirrega GMA	24	14	3	4
North Pendleton GMA	5	1	0	0
Cannawigara GMA	4	4	0	2
Shaugh GMA	3	1	0	0
Zone 8A GMA	1	11	0	0
Tatiara GMA	7	3	0	1
Tatiara PWA	**75**	**50**	**3**	**21**
Other Areas	41	25	15	82
All Models	116	75	18	103

4.4.3 Overall confidence level

In order to evaluate the overall confidence level classification, the matrix shown in Table 4.4 was applied. For observation wells where no trend classification was assessed due to lack of time-series data, no overall classifications were assessed. The classification for all wells are summarised in Table 4.7. The most frequent confidence classification was 'High' in all areas (with the exception of Cannawigara which had an equal number of 'Medium' classifications) but there are also areas with 'Medium' and 'Low' confidence. It should be noted that there are a limited number of observation wells available in the GMAs of Shaugh, North Pendleton, Cannawigara and Zone 8A and this confidence rating may not be representative of the entirety of the GMAs (i.e. data-poor areas). The observations with a 'Low' confidence in the Stirling, Wirrega and Willalooka GMA were due to the 'Poor' residuals found for some wells rather than the trend and variability classification (with the exception of WRG109 which appears to be overly influenced by extraction and WRG026 and WRG020 whose groundwater level trends both reflect the influence of altered recharge rates after land clearance which is not simulated in the model).

The locations and confidence classification for each observation well are shown spatially in Figure 4.15. There are areas with 'Low' confidence in the eastern part of the Stirling GMA, the southern part of the Willalooka GMA and the western part of the Wirrega GMA. These are areas where the groundwater levels are overestimated (in the northern areas) and underestimated (in the southern areas) by more than +/- 2 m while the trends and variability are generally good to reasonable (with three exceptions noted above). Although a 'Low' confidence rating is applied to these wells, the acceptable trends and behaviour of most of these simulated groundwater levels should also be noted (i.e. the simulated response of the aquifer in these locations is acceptable). This means that any future projections of groundwater levels should be compared relative to the simulated levels rather than observed levels in these areas (i.e. with respect to possible resource condition limits, see Chapter 6).

Overall the Tatiara PWA has a 'High' confidence for 52% of observation wells, a 'Medium' confidence for 19% of wells and a 'Low' confidence for 15% of wells with the confidence classification not assessed for a further 14% of wells due to short groundwater level datasets. It is important to consider both the areas of lower and higher confidence discussing the ability of the model to make predictions into the future and subsequent determination of resource condition limits and acceptable extraction limits.

Table 4.7. Confidence level classification for each GMA

Area	Confidence level classification				
	High	*Medium*	*Low*	*N/A*	*Most frequent*
Stirling GMA	14	7	8	11	High
Willalooka GMA	10	2	6	3	High
Wirrega GMA	23	10	8	4	High
North Pendleton GMA	5	1	0	0	High
Cannawigara GMA	4	4	0	2	High-Medium
Shaugh GMA	3	1	0	0	High
Zone 8A GMA	11	0	1	0	High
Tatiara GMA	8	2	0	1	High
Tatiara PWA	78	27	23	21	High
Other Areas	49	16	16	82	High
All Models	127	43	39	103	High

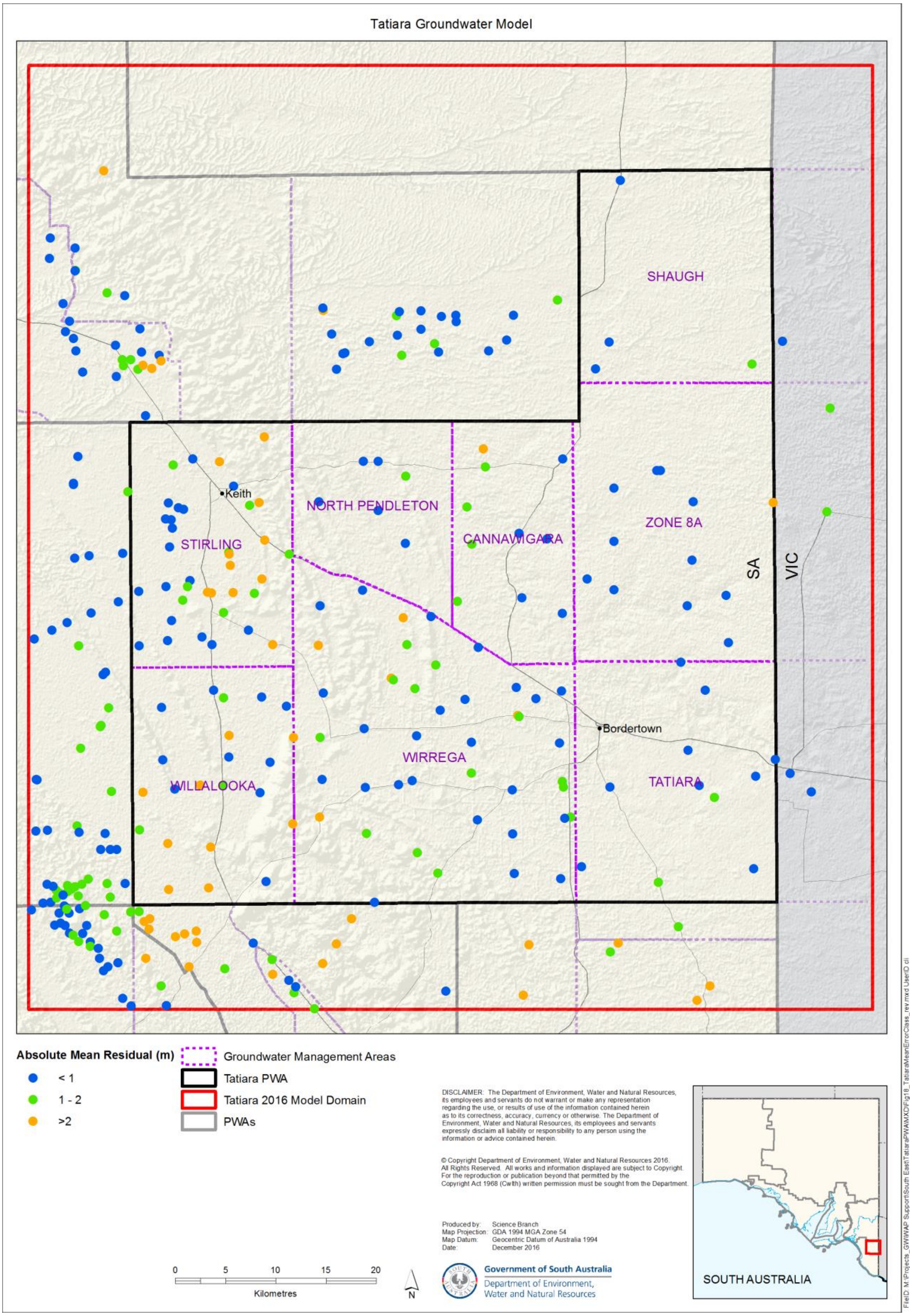

Figure 4.13. Spatial distribution of mean residuals for each observation well used in the calibration period

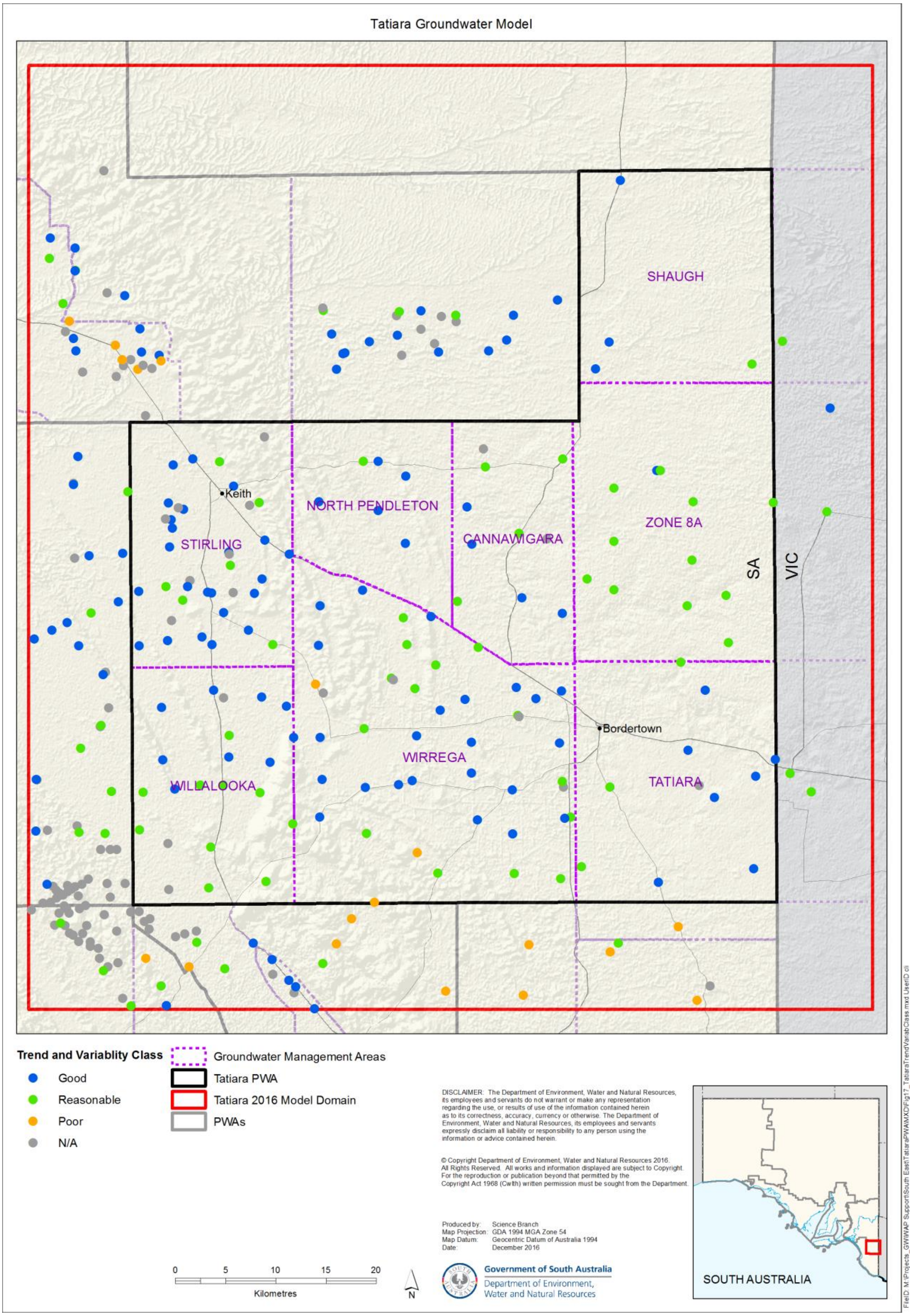

Figure 4.14. Spatial distribution of groundwater trend and variation classification

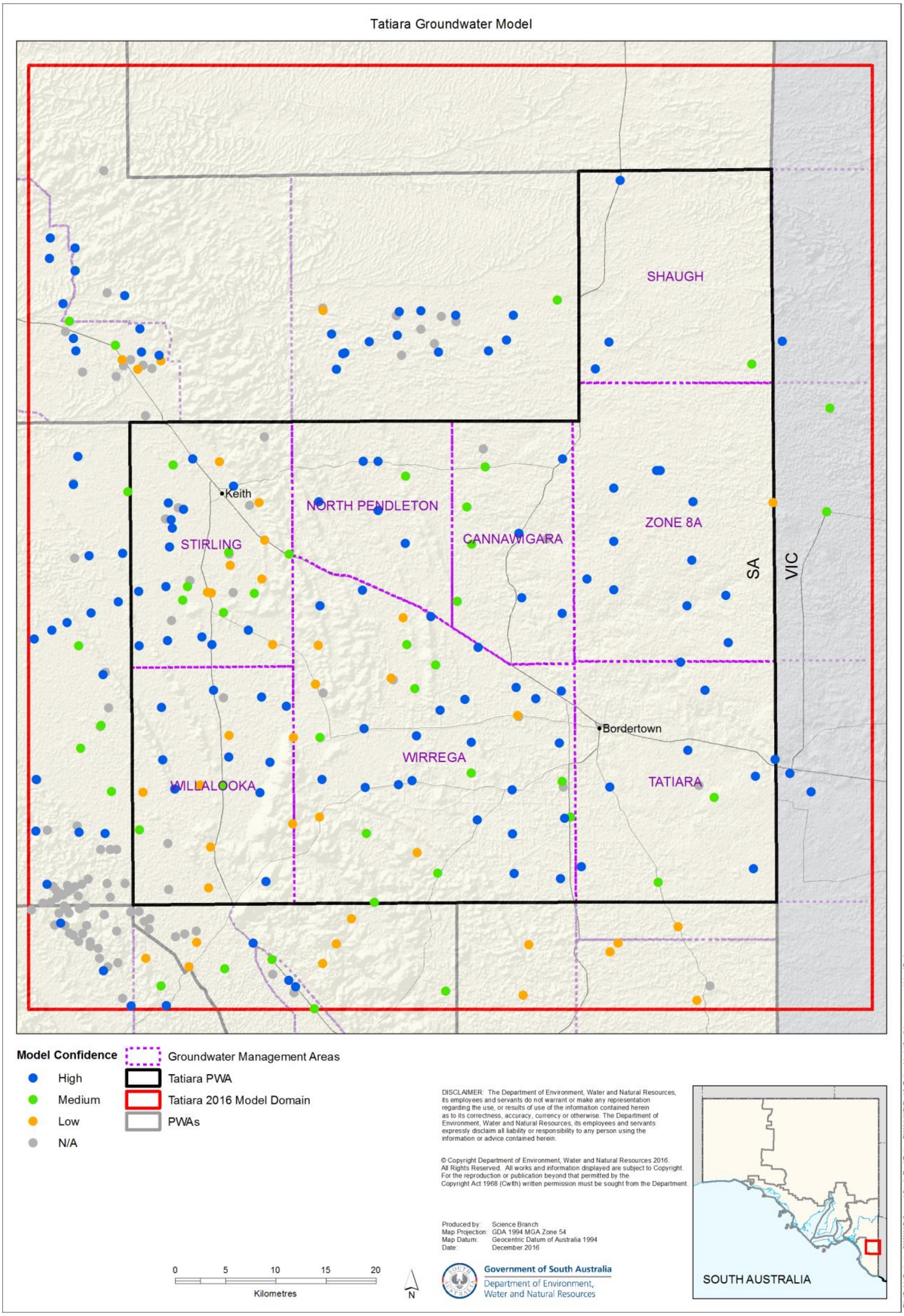

Figure 4.15. Spatial distribution of overall confidence level classification

5 Uncertainty and parameter sensitivity

5.1 Overview

Model uncertainty and parameter sensitivity are important considerations when assessing whether or not a model is fit for purpose. A fit-for-purpose model does not necessarily require every hydrogeological process to be simulated accurately or necessarily captured at all. However, we consider an appropriate balance to have been struck between adding model complexity and achieving practical outcomes with the Tatiara model within the constraints of the project timeline. Different types of uncertainty and sensitivity are discussed in the following sections, while the model capabilities and limitations are outlined in Section 7.

5.2 Parameter and predictive uncertainty

Parameter uncertainty arises from two main sources: the necessary simplification of a heterogeneous reality into regionally-representative parameters, and measurement error (Doherty et al., 2010). Predictive uncertainty arises from the inability of simplified parameters to result in the true prediction of reality and also the measurement error of calibration targets from which the parameters are estimated (Doherty et al., 2010) in addition to simplifications made in the governing equations and numerical error. In light of this, once a model has been calibrated it is possible to estimate the parameter uncertainty and perform a predictive uncertainty analysis. This can be done by creating a large number of randomized parameter combinations (within their nominated uncertainty) which result in similarly "calibrated" models (i.e. similar residual statistics, hydrograph behaviour and mass balances) but may result in different predictions (e.g. rates of groundwater declines). The result of this analysis allows us to quantify for example, the risk of a resource condition limit being exceeded based on the 5th and 95th percentiles of predictions made by alternative but similarly "calibrated" models. We suggest that the predictive uncertainty of each model presented here be assessed in the future, but only if the stakeholders require greater confidence in the model predictions. This could be done using a Calibration-constrained or Null-Space Monte Carlo analysis (after Doherty et al., 2010) which is beyond the current scope of this project.

In this investigation we have calibrated a small family of three models with differing historical extraction estimates on the coastal plain. This has resulted in three models which have different hydraulic parameter values and behave slightly differently in response to stresses and inputs to the system. How the groundwater system behaves in response to future stresses is captured by the differences between these models and goes some way towards capturing the predictive uncertainty resulting from historical extraction assumptions, but is far from a formal predictive uncertainty analysis.

5.3 Parameter sensitivity

Parameter sensitivity has been assessed using the results of a single PEST iteration using the final calibrated parameter values (Doherty, 2012). The sensitivity is derived through the development of the Jacobian matrix which is the result of varying each parameter value and assessing the impact on the objective function. The sensitivity is defined as the change in the objective function divided by the change in the parameter value.

The sensitivity of the model to each parameter is shown in Figure 5.1. The most sensitive parameter is the steady state recharge multiplier which, in combination with hydraulic conductivity values, sets the initial heads of the transient model. The sum of the 61 transient recharge multipliers are presented as the next most sensitive parameter which is expected since recharge was seen to drive the changes in storage seen in the groundwater balance. Each transient recharge multiplier has an individual sensitivity of less than 1E-5 because they do not directly influence observations for the entire calibration period. The hydraulic conductivity values from zones 8, 9, 5 and 11 are the next most sensitive parameters: they are found in the northern section of model domain and control the regional throughflow received by the northern part of the coastal plain. The hydraulic conductivity values from zones 7, 2, 17, 14, 13, 6 and 18 are the next most sensitive parameter values and are located in the central and south of the model domain (see locations shown in Figure 3.5 and Figure 3.6).

The specific yield values for the Padthaway formation in the Wirrega, Willalooka and Stirling GMAs are the most sensitive S_y values as they influence seasonal variation and rates of decline observed in these areas (i.e. zones 3, 7 and 1). The high hydraulic conductivity values representing the western part of the coastal plain and Padthaway Formation (zones 3, 1 and 15) were not particularly sensitive compared with other hydraulic conductivity zones. These parameters consistently pushed at the upper bound of 1000 m/d during all PEST iterations. In contrast the K values of zones 2 and 5 (located in and adjacent to the overestimated heads in the Stirling GMA) and are quite sensitive parameters which would likely play a role in reducing the heads in this area. Since these zones were representative of the Bridgewater and Coomandook formations however, they were limited at a value of 300 m/d as an upper bound. Higher values may have aided in the calibration of observation well in this area but would be considered unrealistically high. Overall it can be seen that hydraulic conductivity parameters are more sensitive than specific yield parameters, the remainder of which are all less than approximately 5E-3 and are not discussed further.

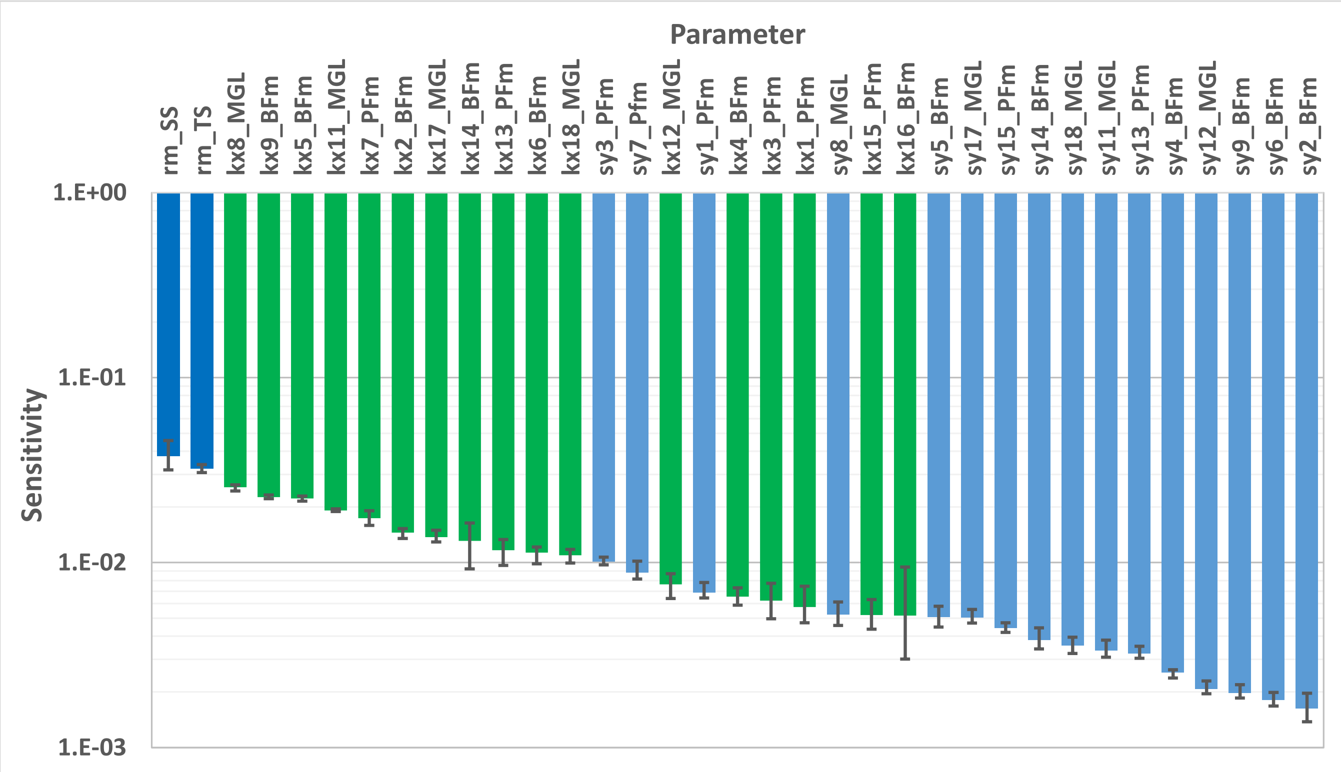

Figure 5.1. Average parameter sensitivity for all three models with error bars showing the minimum and maximum sensitivities. Dark blue bars are related to recharge parameters, green bars are horizontal hydraulic conductivity parameters while lighter blue bars are specific yield parameters.

5.4 Model structural uncertainty

Structural uncertainty (related to model construction and/or conceptualization) has not been investigated within the scope of this modelling study. It should be noted however that there are a number of assumptions which have an unknown influence on the model results as a consequence. These primarily include the:

- Simplification of the model into two vertically discretised layers – the vertical variability of aquifer properties is currently not well characterised or represented by observation wells and so was not included in the model

- Bottom surface elevations – based on interpolated data from a limited number of hydrostratigraphic logs which if significantly different, could cause large scale differences in groundwater flow patterns and levels
- Vertical flux to or from underlying units the basement rock granites or other units on the coastal plain which underlie the poorly described bottom elevation of the MGL and also the Ettrick Marl, Buccleuch Formation or Renmark Group which are clay dominated units (present mostly beneath the Mallee highlands)
- Uniform soil parameters of the unsaturated zone profiles used to simulate recharge (through 5 and 20 m profiles in the coastal plain and Mallee highlands respectively) – which would primarily influence the lag time between rainfall and recharge.

Significant additional effort would need to be made including drilling programs, further data collection and analysis for these and other sources of structural uncertainty to be characterised and then investigated though exploratory model simulations. The structural assumptions made in this version of the models are considered to be reasonable and robust given the data available and the limited scope of the modelling study (i.e. without conducting extensive hypothetical testing of each structural assumption).

6 Scenarios

The three calibrated groundwater models are used to investigate the potential impacts of future groundwater extraction and climate change scenarios within the Tatiara PWA. Four extraction scenarios have been combined with both high and intermediate carbon emissions scenarios from Global Climate Models using statistically downscaled SA Climate Ready datasets. Through the application of each calibrated groundwater model to all combinations of extraction and climate scenarios, there are 72 future projections of groundwater conditions. These are synthesised into eight groups each containing nine realisations of possible futures that are further described below.

Model results are presented as projected groundwater balances and hydrographs and discussed in detail in Section 6.2. Implications for groundwater management are discussed in Section 6.3, with reference to a series of possible resource condition limits (RCLs) presented in Cranswick and Barnett (2017).

6.1 Scenario descriptions

6.1.1 Extraction scenarios

Four extraction scenarios have been developed based on recent groundwater extraction and allocation data with consultation with stakeholders and NR SE. The spatial distribution of the extraction wells is that of current conditions (S3 below), and a spatially-uniform multiplier is applied to current extraction rates to create future extraction rates. The rates described below are those of the Tatiara PWA but the same multipliers have been applied to extraction wells outside of the PWA within the model domain:

- **S1 Full allocation extraction** (138.1 GL) – 2016/17 allocation data after removal of carryover totals;
- **S2 Periodic extraction** (101.9, 81.5, 61.1 GL) – current extraction (S3) as a base rate that is increased by 25% or decreased by 25% if spring-summer rainfall is below or above the 25th and 75th percentiles respectively at the Keith weather station (25507);
- **S3 Current extraction** (81.5 GL) – average of 2013/4, 2014/5 and 2015/6 metered data
- **S4 Lower extraction** (61.1 GL) – current use reduced by 25%

It should be noted that delivery supplements are counted as groundwater extraction in the model and any previously assumed loss is included as irrigation recharge (i.e. such that it is not double counted).

6.1.2 Climate scenarios and dataset selection

Charles and Fu (2015) have summarized the statistically downscaled climate projections for selected South Australian weather stations in each Natural Resources Management region. These projections were calibrated to rainfall station data with the regional-scale climate forcing simulated by selected GCMs (CSIRO and BoM, 2015). The projected changes of decreasing rainfall and increasing potential evapotranspiration for the South East NRM region are reported as 20-year averages centred around 2030, 2050 and 2070 compared to the 1986–2005 historical data period. The mean annual percent change values based on the intermediate emissions scenario (RCP4.5) and the high emissions scenario (RCP8.5) from the six better performing GCMs are shown in Table 6.1 (after Charles and Fu, 2015). It is clear that the largest percentage decreases are seen in spring followed by summer and autumn with smaller changes projected for winter rainfall. Overall the annual rainfall averages change by -5.4% in RCP4.5 and -6.6% in RCP8.5 by 2050 compared to the 1986–2005 baseline.

There are 100 realisations of possible futures for each weather station as projected by each of the 15 GCMs under two emissions scenarios. In order to select a reasonable representation of possible futures we have conducted a climate futures analysis (after Whetton et al., 2012), focusing on the "better performing" 6 GCMs as assessed by Charles and Fu (2015) for South Australia. From this analysis we have selected the projections of IPSL-CM5B-LR for the intermediate emissions scenario and CNRM-CM5 for the high emission scenario. The climate stations located within the Tatiara model domain for these GCMs are shown in Figure 6.1 and it can be seen that the selected GCM projections fall near the centre of the majority of mean projected changes of other GCMs and also fit the general trend of a drying and warming climate into the future.

In the time available for this study, it was not feasible to use all 100 realisations for each of the weather stations relevant to the model. Instead each weather station has had its 10th (drier) 50th (median) and 90th (wetter) percentile mean rainfall realisation selected under each emissions scenario for the above mentioned GCMs. These are considered representative of the possible range of rainfall datasets (i.e. without the computational intensity of running 100 realisations of each model under each scenario i.e. 200 recharge model runs and 2400 groundwater model runs). It should also be noted that the differences between realisations of temperature are considered to have a smaller influence on recharge than change in rainfall and so have not been analysed separately (McCallum et al., 2010).

Table 6.1. South East NRM downscaled projected changes in seasonal rainfall averages from the six better performing GCMs (after Charles and Fu, 2015)

20-year middle	**Intermediate emissions RCP4.5**				
	Annual	*Summer*	*Autumn*	*Winter*	*Spring*
1995	0	0	0	0	0
2030	-3.5	-7.5	-1.8	4.8	-16
2050	-5.4	-3.6	-3.4	0.7	-17.5
2070	-7.4	-5.5	-5.8	0.3	-21.8
2090	-6.5	-5.6	-5.4	3	-22.8
20-year middle	**High emissions RCP8.5**				
	Annual	*Summer*	*Autumn*	*Winter*	*Spring*
1995	0	0	0	0	0
2030	-4.4	-0.4	-3.3	0.4	-14.4
2050	-6.6	-6.8	-3.4	3.2	-24.2
2070	-11.9	-14	-9.2	-0.7	-30.9
2090	-15.9	-18.3	-12.8	-1.3	-40.3

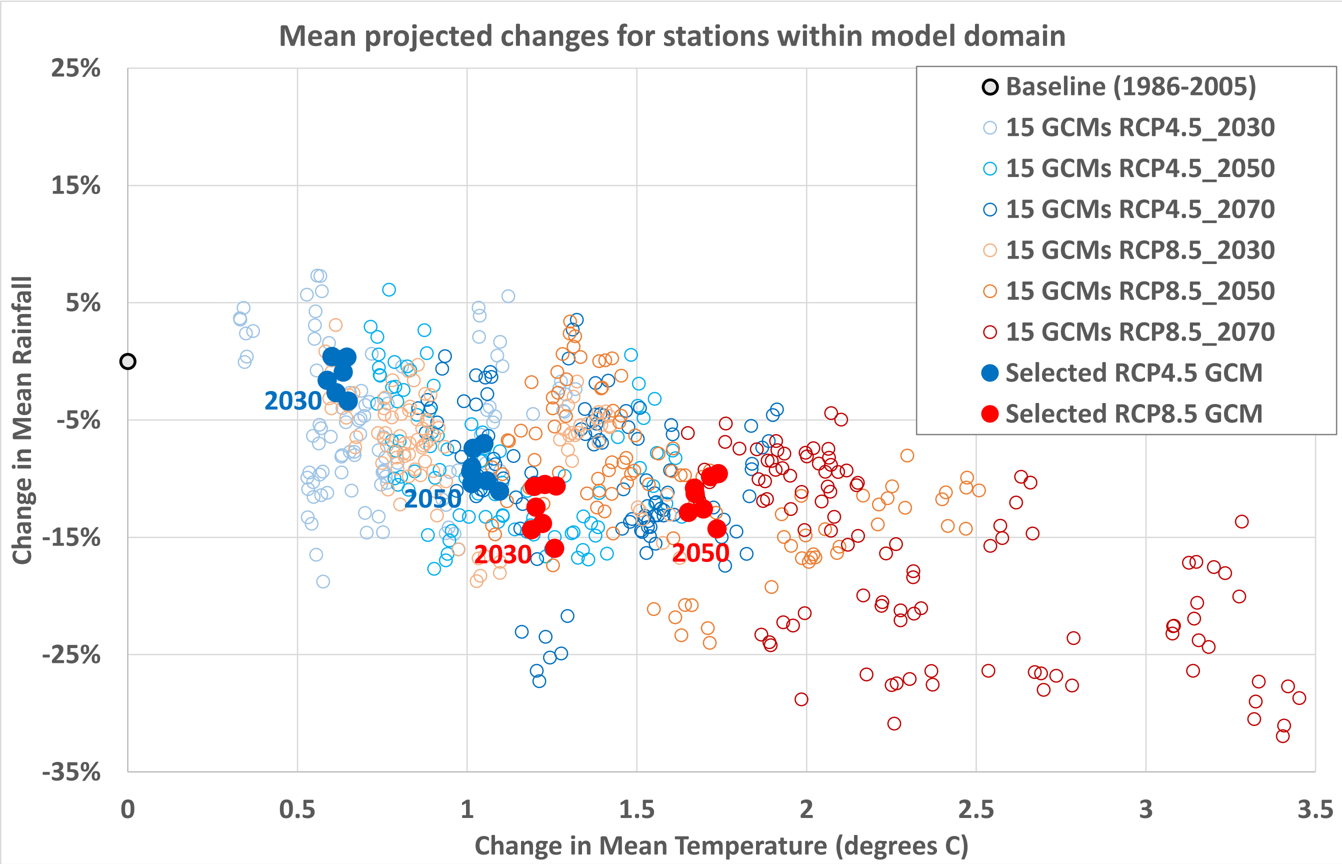

Figure 6.1. Summary of climate futures analysis for 20-year averages centred on 2030, 2050 and 2070 and selected GCMs for intermediate and high emissions scenarios

6.1.3 Presentation of projected hydrographs and groundwater balances

For each groundwater extraction scenario, all three of the calibrated models have been used in combination with two climate scenarios, each containing three climate datasets. This results in a group of nine future projections for each combination of extraction (4) and emissions scenarios (2) and therefore a total of 72 future projections of groundwater levels and groundwater mass balances for all combinations. This results in 8 groups of scenario results which are shown on the bottom row of Figure 6.2. For simplicity, and to capture the range of reasonable possibilities, the average, minimum and maximum groundwater level and groundwater mass balance fluxes have been calculated for each group. These groups each contain nine individual model projections and are labelled according to the extraction scenarios above (i.e. S1, S2, S3 and S4) with an additional H or I for the high (RCP8.5) or intermediate (RCP4.5) emissions climate scenarios respectively (e.g. S2H and S2I). The mass balances are shown in the following Section as figures while mass balance tables and hydrographs are shown in Appendix C and Appendix D–K respectively in Volume 2 of this report. The implications with respect to possible RCLs are presented and discussed in Section 6.2.6.

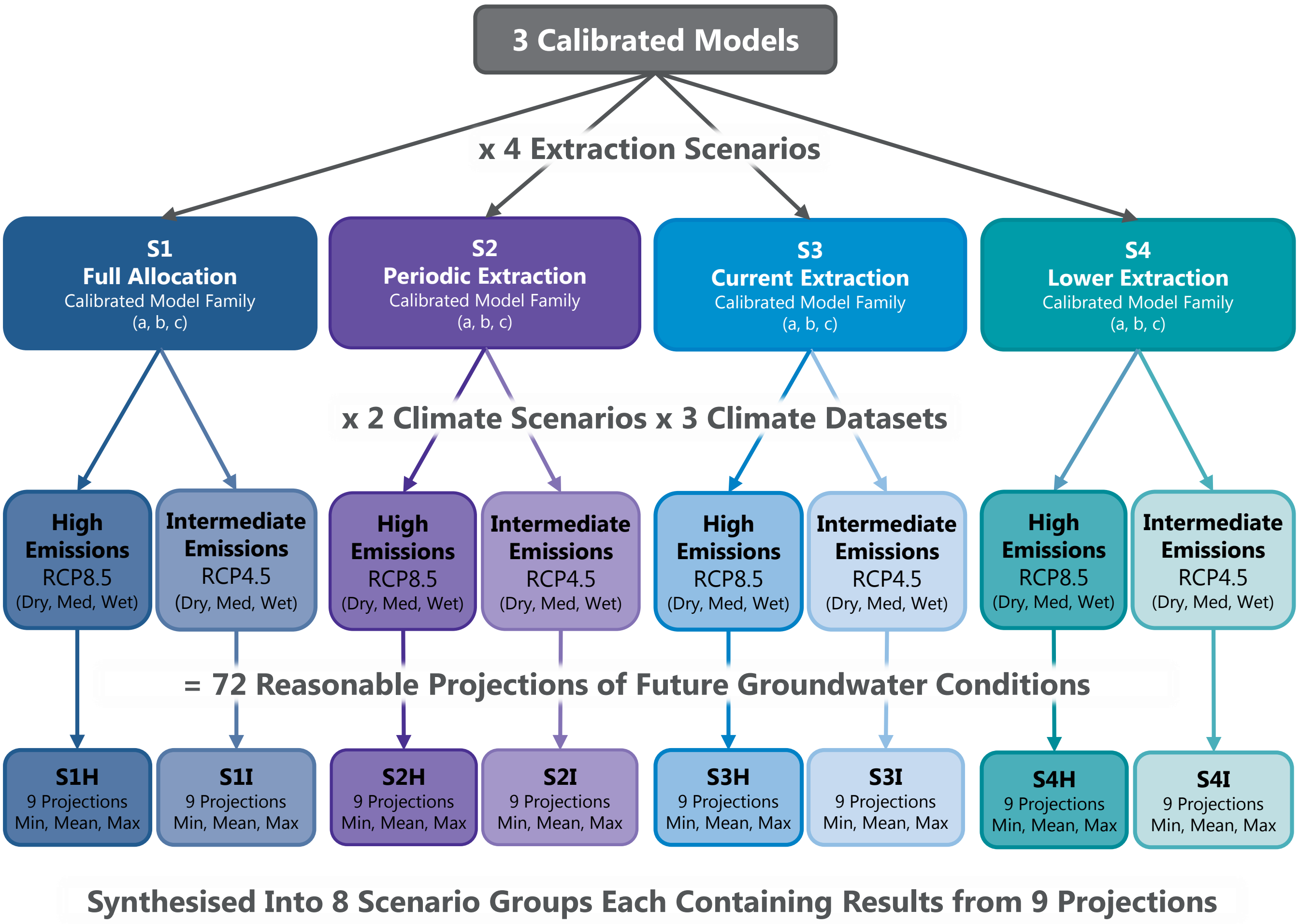

Figure 6.2. Summary of model scenario combinations including three calibrated models, four extraction scenarios, two emission scenarios and three climate datasets for each (3 x 4 x 2 x 3=72)

6.2 Results

The groundwater mass balance projections for all scenario groups are summarised for the Tatiara PWA below and include a selection of hydrographs and 10-year average groundwater mass balance charts for each. Similar analysis for the coastal plain and Mallee highland are shown separately in Appendix C of Volume 2 of this report. The groundwater mass balances fluxes for the Tatiara PWA are summarised in Table 6.2 on the following page and show the range of projections from all calibrated models in combination with each extraction scenario and climate realisations. The average of each time period is shown in bold while the minimum and maximum are shown on either side of that value. These results are discussed firstly in relation to future projections in recharge and then for each extraction scenario.

Table 6.2 10-year average groundwater mass balances for the Tatiara PWA showing minimum, average (bold) and maximum flux values

		Diffuse recharge			Extraction			Storage			Point recharge			Groundwater ET			Inflow			Outflow		
Calibration	Steady State	116	**132**	147	-72	**-82**	-93	0	**0**	0	3	**3**	3	-8	**-10**	-14	18	**21**	24	-57	**-63**	-68
	1986-1995	120	**129**	138	-81	**-92**	-104	6	**-9**	-24	6	**6**	6	-9	**-11**	-15	18	**21**	25	-61	**-62**	-63
	1996-2005	81	**98**	112	-81	**-93**	-105	-25	**-30**	-38	4	**4**	4	-5	**-6**	-7	18	**22**	25	-53	**-55**	-56
	2006-2015	48	**53**	56	-83	**-86**	-88	-49	**-50**	-50	3	**3**	3	-1	**-1**	-1	20	**23**	27	-37	**-41**	-45
S1I	2015-2024	79	**94**	112	-129	**-130**	-131	-28	**-44**	-56	5	**7**	7	0	**-1**	-1	22	**26**	29	-33	**-40**	-46
	2025-2034	83	**92**	108	-124	**-127**	-130	-28	**-39**	-47	5	**7**	10	0	**0**	-1	23	**28**	32	-31	**-39**	-47
	2035-2045	78	**89**	106	-123	**-124**	-127	-29	**-38**	-44	4	**5**	6	0	**0**	0	25	**29**	34	-28	**-36**	-46
S1H	2015-2024	65	**73**	85	-128	**-128**	-129	-54	**-62**	-68	5	**6**	6	0	**0**	0	22	**26**	30	-32	**-38**	-43
	2025-2034	64	**69**	77	-123	**-124**	-127	-54	**-58**	-61	1	**2**	4	0	**0**	0	24	**28**	32	-27	**-33**	-40
	2035-2045	62	**68**	76	-118	**-121**	-124	-42	**-45**	-48	4	**5**	6	0	**0**	0	26	**31**	35	-23	**-28**	-35
S2I	2015-2024	79	**94**	112	-87	**-93**	-97	1	**-13**	-21	5	**7**	7	-1	**-2**	-3	21	**25**	29	-38	**-44**	-50
	2025-2034	83	**92**	108	-91	**-93**	-95	-3	**-16**	-24	5	**7**	10	-1	**-2**	-3	23	**27**	31	-40	**-48**	-58
	2035-2045	78	**89**	106	-91	**-93**	-95	-10	**-20**	-26	4	**5**	6	-1	**-1**	-3	24	**28**	33	-38	**-47**	-58
S2H	2015-2024	65	**73**	85	-89	**-89**	-91	-20	**-29**	-36	5	**6**	6	-1	**-1**	-1	21	**25**	29	-36	**-43**	-49
	2025-2034	64	**69**	77	-89	**-89**	-91	-28	**-34**	-39	1	**2**	4	-1	**-1**	-1	23	**27**	31	-36	**-43**	-50
	2035-2045	62	**68**	76	-86	**-90**	-93	-26	**-28**	-31	4	**5**	6	0	**0**	-1	25	**29**	33	-33	**-41**	-49
S3I	2015-2024	79	**94**	112	-84	**-84**	-84	9	**-6**	-18	5	**7**	7	-1	**-2**	-3	21	**25**	29	-39	**-45**	-52
	2025-2034	83	**92**	108	-84	**-84**	-84	-2	**-12**	-20	5	**7**	10	-1	**-2**	-4	23	**27**	31	-43	**-52**	-62
	2035-2045	78	**89**	106	-84	**-84**	-84	-8	**-17**	-23	4	**5**	6	-1	**-2**	-4	23	**28**	32	-43	**-52**	-63
S3H	2015-2024	65	**73**	85	-84	**-84**	-84	-16	**-25**	-31	5	**6**	6	-1	**-1**	-1	21	**25**	29	-38	**-43**	-49
	2025-2034	64	**69**	77	-84	**-84**	-84	-27	**-32**	-35	1	**2**	4	-1	**-1**	-2	23	**27**	31	-38	**-45**	-53
	2035-2045	62	**68**	76	-84	**-84**	-84	-21	**-26**	-29	4	**5**	6	0	**-1**	-1	25	**29**	33	-36	**-43**	-50
S4I	2015-2024	79	**94**	112	-63	**-63**	-63	25	**10**	-2	5	**7**	7	-1	**-2**	-4	21	**25**	28	-43	**-50**	-56
	2025-2034	83	**92**	108	-63	**-63**	-63	6	**-2**	-9	5	**7**	10	-2	**-4**	-9	22	**26**	30	-51	**-60**	-69
	2035-2045	78	**89**	106	-63	**-63**	-63	-2	**-9**	-14	4	**5**	6	-2	**-5**	-10	22	**27**	31	-53	**-61**	-70
S4H	2015-2024	65	**73**	85	-63	**-63**	-63	-1	**-9**	-14	5	**6**	6	-1	**-1**	-2	21	**25**	28	-41	**-47**	-53
	2025-2034	64	**69**	77	-63	**-63**	-63	-17	**-21**	-24	1	**2**	4	-1	**-2**	-3	22	**26**	30	-46	**-54**	-62
	2035-2045	62	**68**	76	-63	**-63**	-63	-13	**-16**	-19	4	**5**	6	-1	**-1**	-2	24	**28**	32	-46	**-53**	-61

6.2.1 Future recharge projections

The climate datasets are applied to the USE recharge model (Morgan et al., 2017) to produce estimates of projected diffuse recharge that are then applied to the groundwater model for the future period (2015–45). The weather stations where data was available were used to create a new climate raster for input into LEACHM rather than the previous climate zones. The recharge model was run for 10 cycles of 30 years and used the last 30 years of data (representing 2015–45). The volume weighted average recharge multiplier for the calibration stress periods were calculated for each model and applied to future projections of recharge. These were 0.80, 0.84 and 0.87 for Models A, B and C respectively.

As an example, the total recharge for Model B within the Tatiara PWA over time are shown in Figure 6.3. It is notable that the RCP4.5 90th percentile dataset results in high recharge that is similar to the relatively wet period from the mid-1980s to mid-1990s. Meanwhile the other datasets for both RCP4.5 and RCP8.5 results in recharge that is comparable or lower than that estimated since the mid-1990s but not as low as the last 10 years (2005–15), which was a decade of unusually low rainfall. It is important to note that these recharge projections represent only 3 of 100 possible SA Climate Ready dataset realisations selected from one GCM from each carbon emissions scenario. Thus any periods of high or low recharge shown for a particular year represent a projection that is statistically possible rather than a prediction.

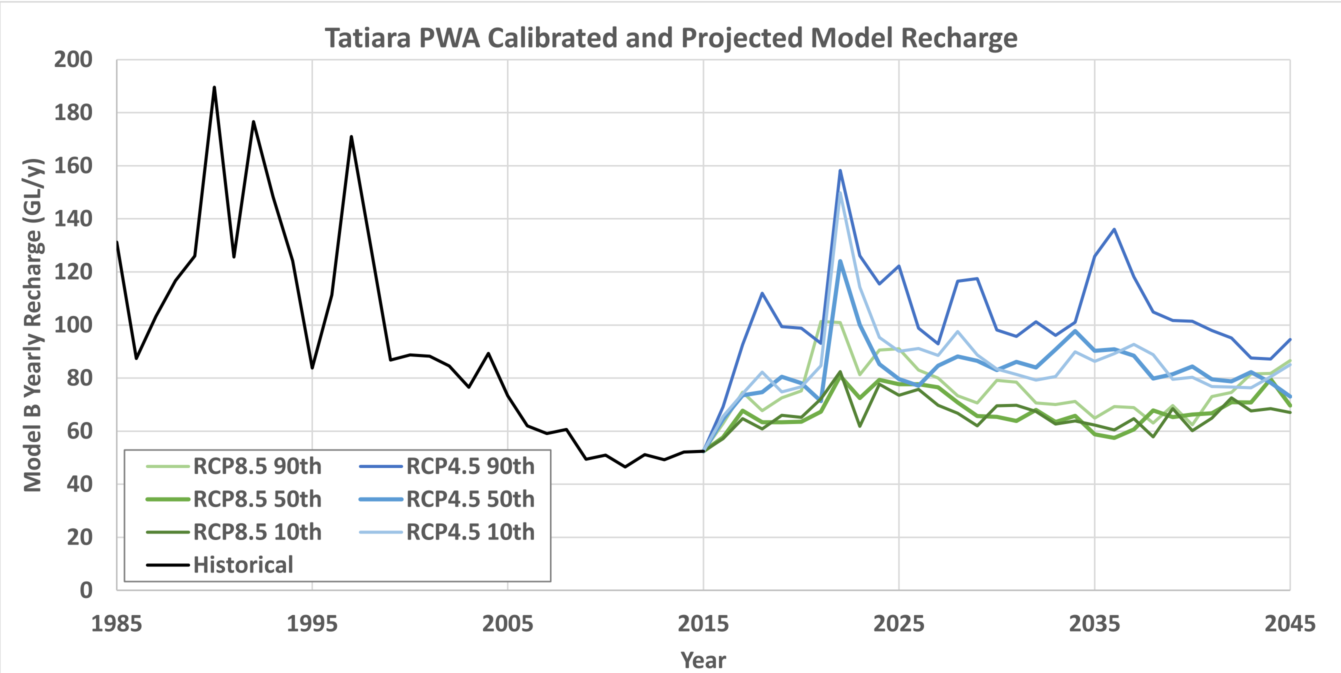

Figure 6.3. Tatiara PWA Model B total recharge for both the historical and six realisations of the future period

The climate zones applied in the future period (created using Thiessien polygons to represent data from 5 rainfall stations) are coarser than those used in the historical period (containing primarily six rectangular climate zones). This difference is likely to have caused some variation in the distribution of recharge across the groundwater model domain after 2015. However the new zones still maintain the regional patterns of increasing PET and decreasing rainfall from the coast to inland areas while more detailed comparisons are made in Morgan et al. (2017). It is recommended that future recharge model applications ensure continuity of climate input methods from historical into projected future periods.

The annual average diffuse recharge decreases over the next 30 years from 94 GL/y down to 89 GL/y in the intermediate emissions scenario and from 73 GL/y down to 68 GL/y in the high emissions scenario. The range of average diffuse recharge is 62–85 GL/y for the high emissions scenario which is greater than the 2006–15 average of 48–56 GL/y. The range of average recharge in the intermediate emissions scenario is 78–112 GL/y which is more like the average recharge from 1996–2005 (81–112 GL/y). Point recharge is more variable and dependent on large rainfall events ranging on average from 4–10 GL/y and 1–6 GL/y for the intermediate and high emissions scenarios respectively

6.2.2 S1 Full allocation extraction

The mass balances for the full allocation scenario with both intermediate and high carbon emission datasets are shown in Figure 6.4 and Figure 6.5 respectively. Under this scenario, groundwater extraction increases to 128–131 GL/y and then reduces slightly as parts of the aquifer become dry over time. The continued reductions in storage (28–56 GL/y and 42–56 GL/y for S1I and S1H respectively) into the future is the result of extraction and other outputs being less than the total inflows to the PWA. Approximately one third to half of extraction is taken from storage. Lateral outflow decreases into the future as storage is depleted and groundwater throughflow slows towards the west while groundwater ET no longer occurs. The slowing of groundwater movement out of the Tatiara PWA would likely result in more rapid salinity increases on the coastal plain due to continued irrigation recycling. The inflow into the system is seen to increase into the future in response to the depletion of the unconfined aquifer, but this increase is not great enough to replace the loss of storage. It is possible that a new equilibrium would be reached for this extraction rate some time in the future but not without continued loss of storage. The diffuse recharge inputs (even when combined with point recharge and lateral inflow) are less than the extraction volumes for this scenario.

A selection of nine hydrographs are shown in Figure 6.6 which are considered approximately spatially representative within the Tatiara PWA (e.g., the top right hydrograph represents projected groundwater levels in the north-east of the Tatiara PWA while actual locations are shown in Figure 3.11). Groundwater levels are seen to decline in all scenario combinations across the entire Tatiara PWA (with the exception of the 90th percentile for the intermediate emissions scenario for the northwestern part of the coastal plain which show stable to slight declining trends). From 2015–45 water level declines are approximately 0–5 m on the coastal plain and 1–3 m in the Mallee highlands. The largest declines are projected to occur in the central part of the coastal plain within the Wirrega GMA. There is approximately a 1 m difference in the total declines projected in between the intermediate and high emissions scenarios.

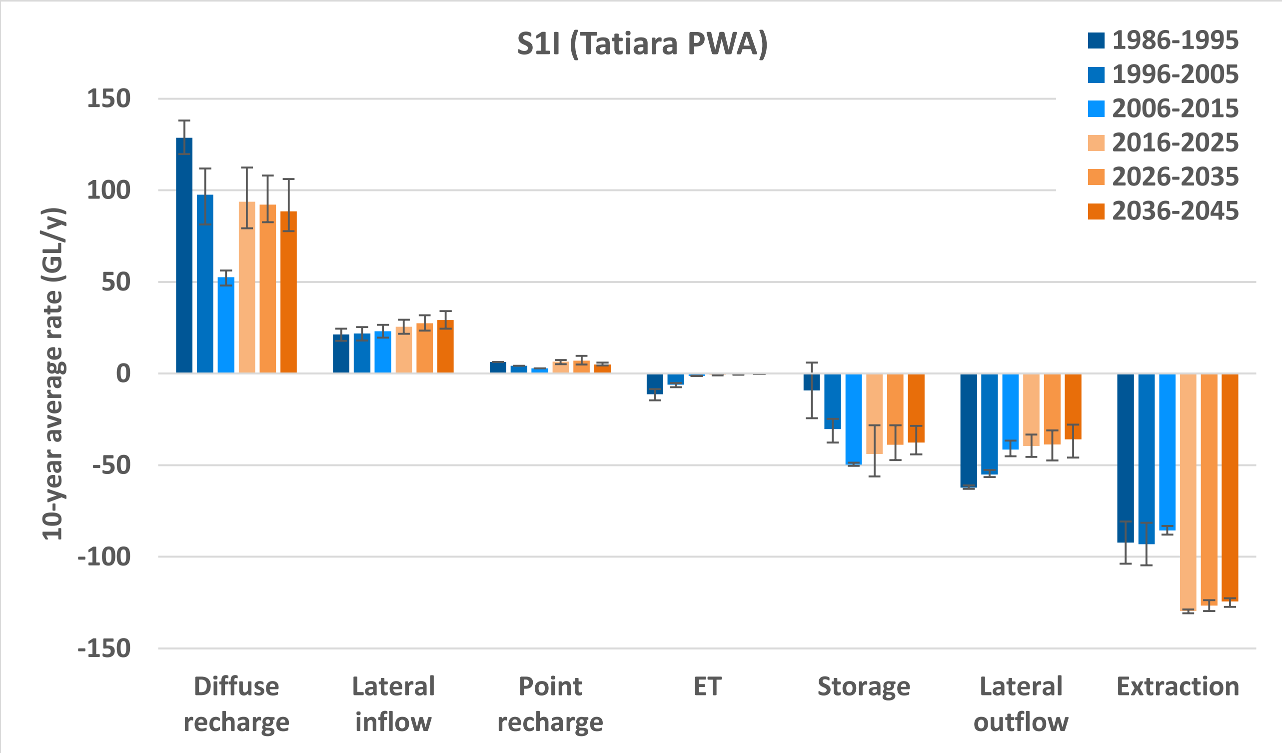

Figure 6.4. Groundwater mass balance for S1 (Full allocation) with intermediate carbon emissions scenarios

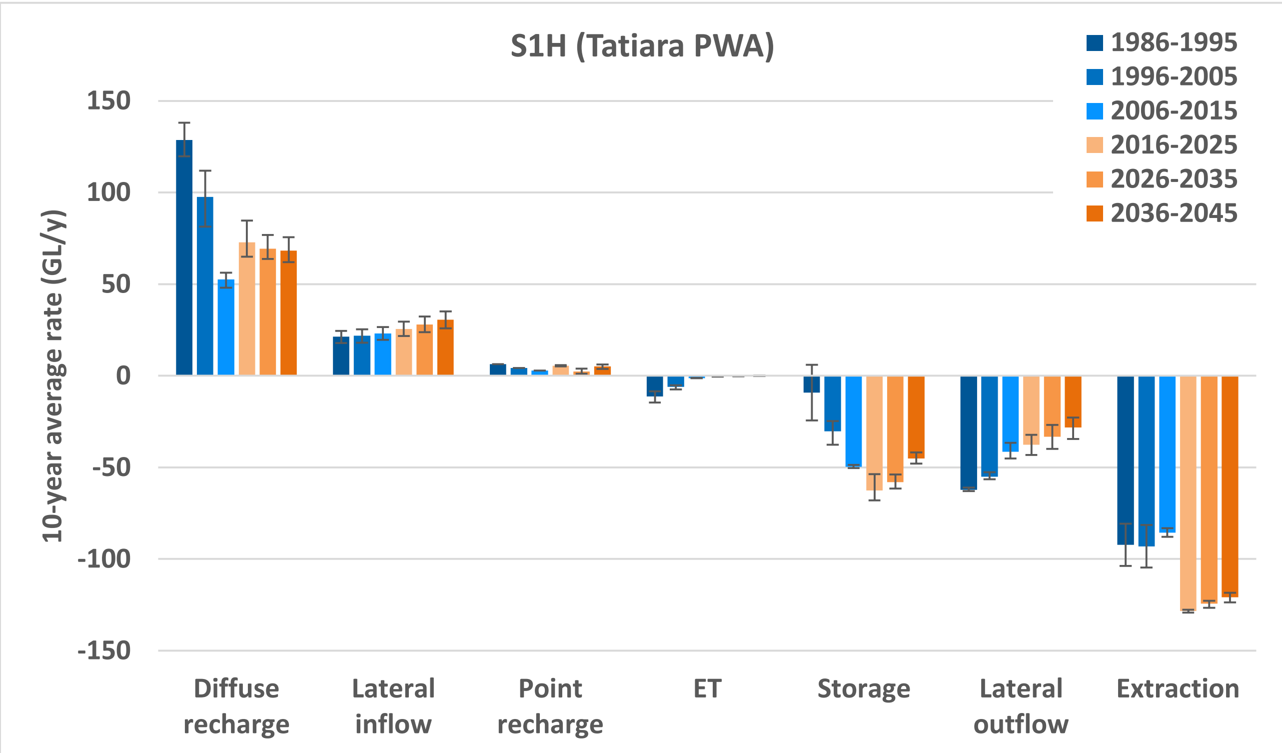

Figure 6.5. Groundwater mass balance for S1 (Full allocation extraction) with high carbon emissions scenarios

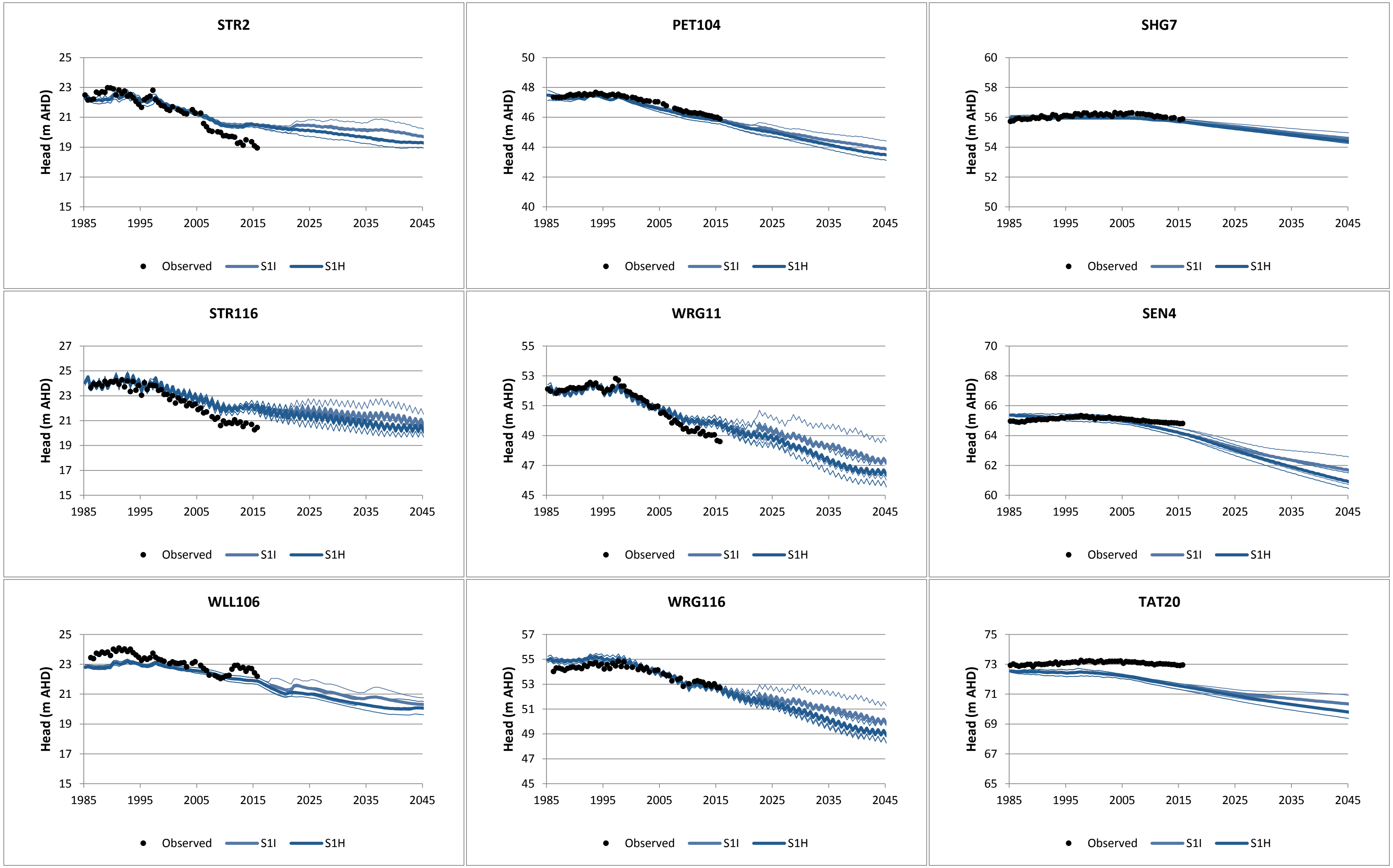

Figure 6.6. Selected hydrographs from S1 (Full allocation) including both intermediate and high carbon emission scenario projections

6.2.3 S2 Periodic extraction

The mass balance for the periodic extraction scenario with both intermediate and high carbon emission datasets are shown in Figure 6.7 and Figure 6.8 respectively. Groundwater extraction increases to average 93 and 89 GL/y for S2I and S2H respectively, and continues at similar rates over time. The continued reductions in storage (0–26 GL/y and 20–39 GL/y for S2I and S2H respectively) into the future is the result of extraction and other outputs being less than the total inflows to the PWA. These losses from storage are less than the loss occurring from 2006–15 but are still show that the groundwater resource is being depleted. Groundwater extraction is higher on average in S2I (87–97 GL/y) than S2H (86–93 GL/y) due to the greater frequency of low rainfall in the climate projections used. The averages of these rates are similar at 93 and 89 GL/y for S2I and S2H respectively and result in similar impacts on the groundwater balance. Lateral outflow remains approximately constant in S2H while it increases in S2I with groundwater ET occurring at very low rates. The lateral outflow observed in these scenarios is similar to that of the 2006–15 period suggesting that rising salinity trends would be likely to continue at the historical rates on the coastal plain due to continued irrigation recycling. The inflow into the system is seen to increase into the future in response to the depletion of the unconfined aquifer, but this increase is not great enough to replace the loss of storage. It is possible that a new equilibrium would be reached for this extraction rate some time in the future but not without continued loss of storage. The diffuse recharge inputs (when diffuse recharge is combined with point recharge and lateral inflow) are greater than the extraction volumes for this scenario but not greater than the total of all outflows (i.e. including throughflow and groundwater ET).

A selection of nine hydrographs are shown in Figure 6.9 which are considered approximately spatially representative within the Tatiara PWA (e.g., the top right hydrograph represents projected groundwater levels in the north-east of the Tatiara PWA while actual locations are shown in Figure 3.11). Groundwater levels are seen to stabilise on the western side of the coastal plain but show continued declines further to the east. From 2015–45 water level declines are approximately 0–2 m on the eastern part of the coastal plain and 1–2 m in the Mallee highlands. The largest declines are projected to occur in the southeast of the coastal plain within the Wirrega GMA as well as adjacent GMAs of Zone 7A and Tatiara in the Mallee highlands. The declines on the Mallee highlands are likely a delayed response to the decline in coastal plain groundwater levels from the mid-1990s to 2015. There is approximately a 1 m difference in the total declines projected in between the intermediate and high emissions scenarios.

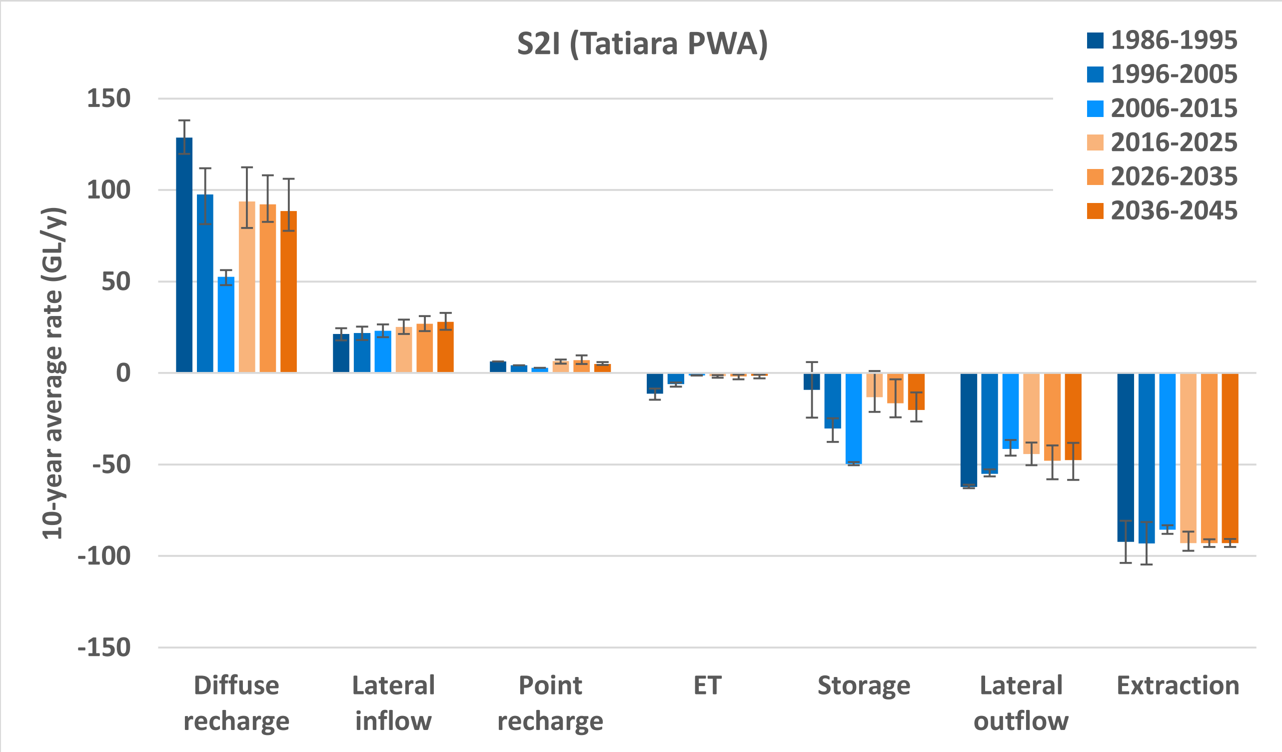

Figure 6.7. Groundwater mass balance for S2 (Periodic extraction) with intermediate carbon emissions scenarios

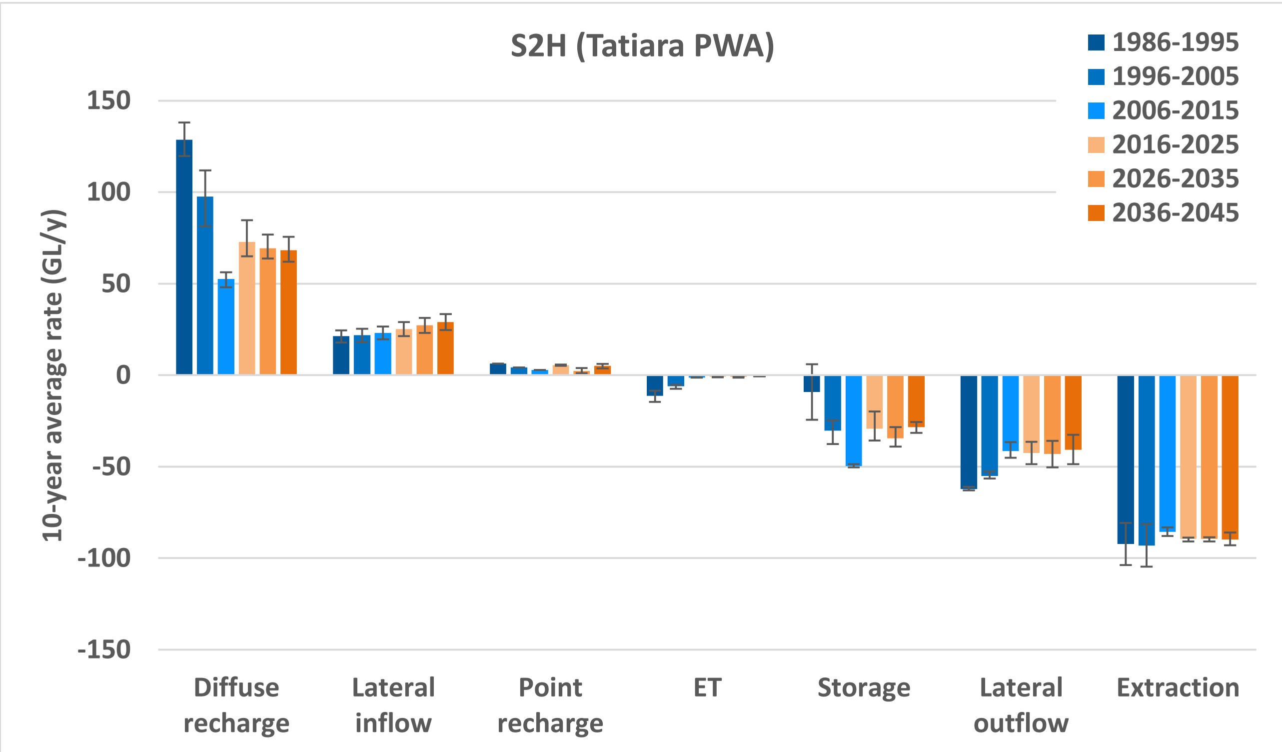

Figure 6.8. Groundwater mass balance for S2 (Periodic extraction) with high carbon emissions scenarios

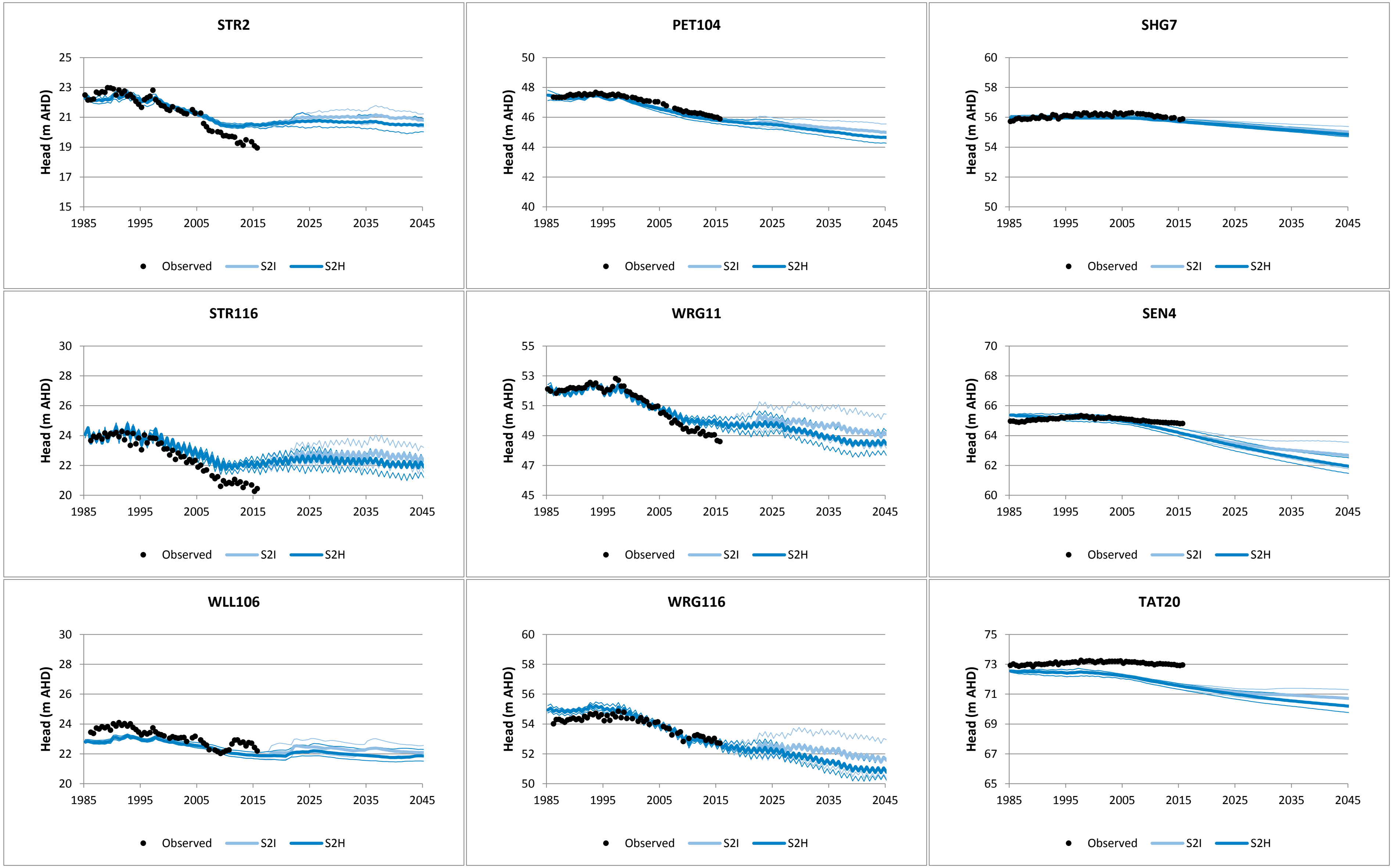

Figure 6.9. Selected hydrographs from S2 (Periodic extraction) including both intermediate carbon emission scenario projections

6.2.4 S3 Current extraction

The mass balance for the current extraction scenarios with both intermediate and high carbon emission datasets are shown in Figure 6.10 and Figure 6.11 respectively. Groundwater extraction continues at similar rates to the 2006–15 period at 84 GL/y and continues at that rate over time. Continued reductions in storage occur in S3H (16–36 GL/y) while there is some recovery overall in S3I for the first 10-year average and then small losses for the remaining two average periods (2–23 GL/y). Extraction at this rate (84 GL/y) combined with the other outputs are similar to or moderately less than the total inflows to the PWA. The losses from storage in S3H are less than the loss occurring from 2006–15 but similar to the 1996–2005 average, while S3I storage loss is more like the 1986–95 average indicating that the groundwater resource continues to be depleted overall. Lateral outflow remains approximately constant in S2H while it increases in S2I with groundwater ET occurring at very low rates. The lateral outflow observed in these scenarios is similar to that of the 2006–15 period but increases over time in S3I to rates similar to pre-2006 averages. This suggests that rising salinity trends would be likely to continue at the historical rates on the coastal plain due to continued irrigation recycling. The inflow into the system is seen to increase only slightly into the future in response to the depletion of the unconfined aquifer, but this increase is not great enough to replace the loss of storage. It is possible that a new equilibrium would be reached for this extraction rate some time in the future but not without continued loss of storage. The diffuse recharge inputs (when combined with point recharge and lateral inflow) are greater than the extraction volumes for this scenario but not greater than the total of all outflows (i.e. including throughflow and groundwater ET).

A selection of nine hydrographs are shown in Figure 6.12 which are considered approximately spatially representative within the Tatiara PWA (e.g. the top right hydrograph represents projected groundwater levels in the northeast of the Tatiara PWA while actual locations are shown in Figure 3.11). Groundwater levels are seen to stabilise or rise on the western side of the coastal plain but show either stable or slightly declining trends further to the east. From 2015–45 water level declines are approximately 0–2 m in both the eastern part of the coastal plain and the Mallee highlands. The largest declines are projected to occur in the southeast of the coastal plain within the Wirrega GMA as well as adjacent GMAs of Zone 7A and Tatiara in the Mallee highlands. The declines on the Mallee highlands are likely a delayed response to the decline in coastal plain groundwater levels from the mid-1990s to 2015. There is approximately a 1 m difference in the total declines projected in between the intermediate and high emissions scenarios.

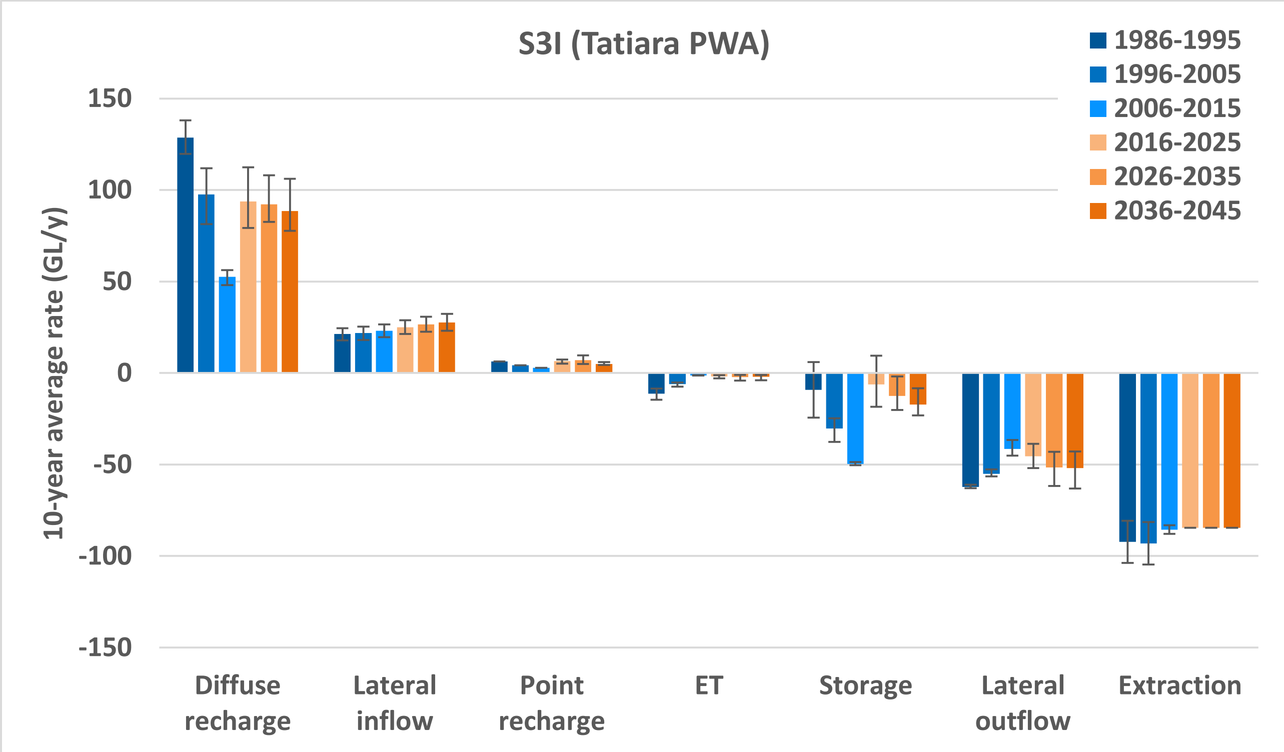

Figure 6.10. Groundwater mass balance for S3 (Current extraction) with intermediate carbon emissions scenarios

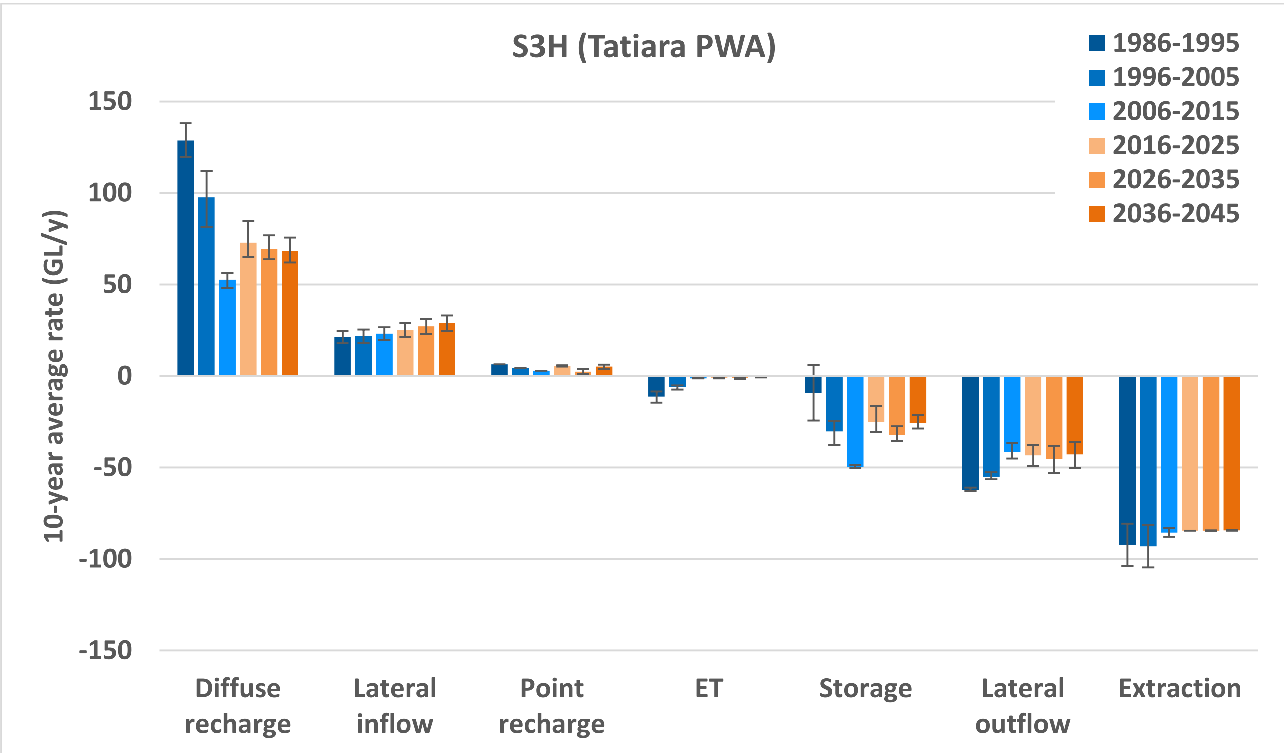

Figure 6.11. Groundwater mass balance for S3 (Current extraction) with high carbon emissions scenarios

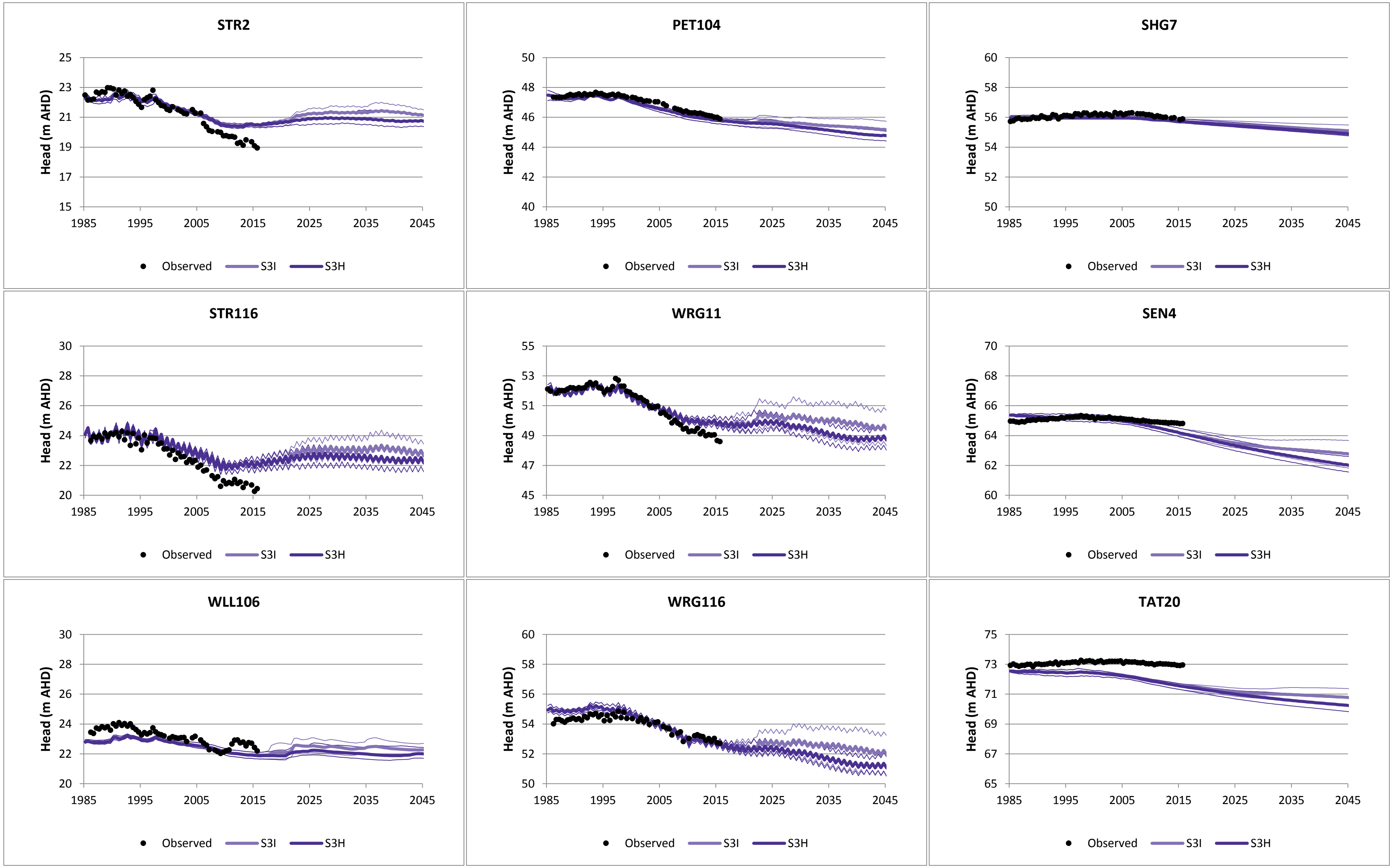

Figure 6.12. Selected hydrographs from S3 (Current extraction) including both intermediate carbon emission scenario projections

6.2.5 S4 Lower extraction

The mass balance for the lower extraction scenarios with both intermediate and high carbon emission datasets are shown in Figure 6.13 and Figure 6.14 respectively. Groundwater extraction is 63 GL/y which is 20–25 GL/y lower than rates of the 2006–15 period. Continued reductions in storage occur in S4H (1–24 GL/y) while there is recovery or only minor depletion overall in S4I. Extraction at this rate (63 GL/y) combined with the other outputs are similar to or slightly less than the total inflows to the PWA. The losses from storage in S4H are between the 1986–95 and 1996–2005 averages and similar to the 1986–95 average for S4I indicating that the groundwater resource is continues to be depleted overall only in the high carbon emissions scenario. Lateral outflow increases over time for S4H and S4I while groundwater ET increases only in S4I (ranging from 1–10 GL/y) and remains small in S4H (1–3 GL/y). The lateral outflow observed in these scenarios is similar to 1986–95 and 1996–2005 averages but increases over time more markedly in S4I. This suggests that rising salinity trends could possibly be lessened compared to recent historical rates on the coastal plain due to continued irrigation recycling but greater throughflow across the area. The inflow into the system is seen to increase only slightly into the future in response to the historical depletion of the unconfined aquifer, but this increase is not great enough to replace the loss of storage. It is possible that a new equilibrium would be reached under this extraction rate some time in the future but not without continued loss of storage under S4H. The diffuse recharge inputs (when combined with point recharge and lateral inflow) are greater than the extraction volumes for this scenario but not greater than the total of all outflows (i.e. including throughflow and groundwater ET) in S4H while the groundwater system of S4I is seen to recover overall.

A selection of nine hydrographs are shown in Figure 6.15 which are considered approximately spatially representative within the Tatiara PWA (e.g., the top right hydrograph represents projected groundwater levels in the northeast of the Tatiara PWA while actual locations are shown in Figure 3.11). Groundwater levels are seen to rise and stabilise on the western side of the coastal plain but show slightly rising and then stable trends further to the east. From 2015–45 water level declines are approximately 0–2 m in both the eastern part of the coastal plain and the Mallee highlands. The largest declines are projected to occur adjacent to the Wirrega GMA in the Mallee highlands (i.e. Zone 7A and Tatiara GMAs). The declines on the Mallee highlands are likely a delayed response to the decline in coastal plain groundwater levels from the mid-1990s to 2015. There is approximately a 1 m difference in the total declines projected in between the intermediate and high emissions scenarios.

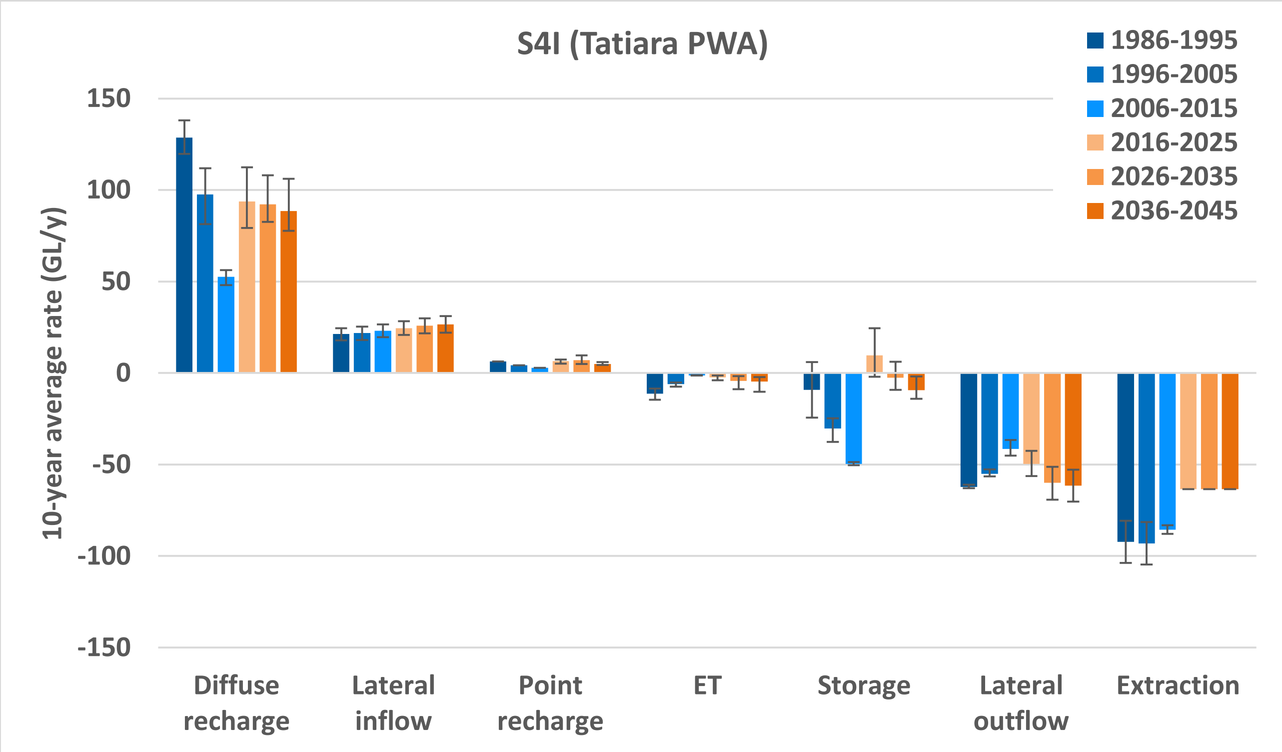

Figure 6.13. Groundwater mass balance for S4 (Lower extraction) with intermediate carbon emissions scenarios

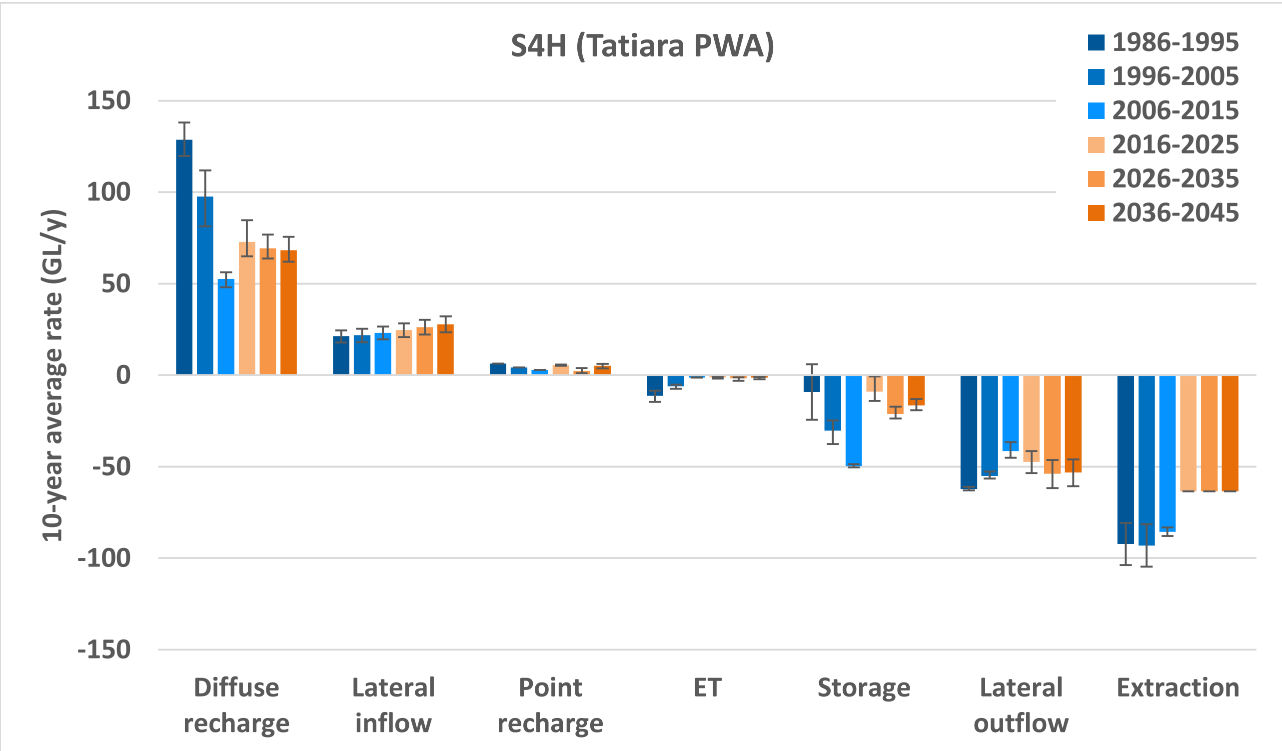

Figure 6.14. Groundwater mass balance for S4 (Lower extraction) with high carbon emissions scenarios

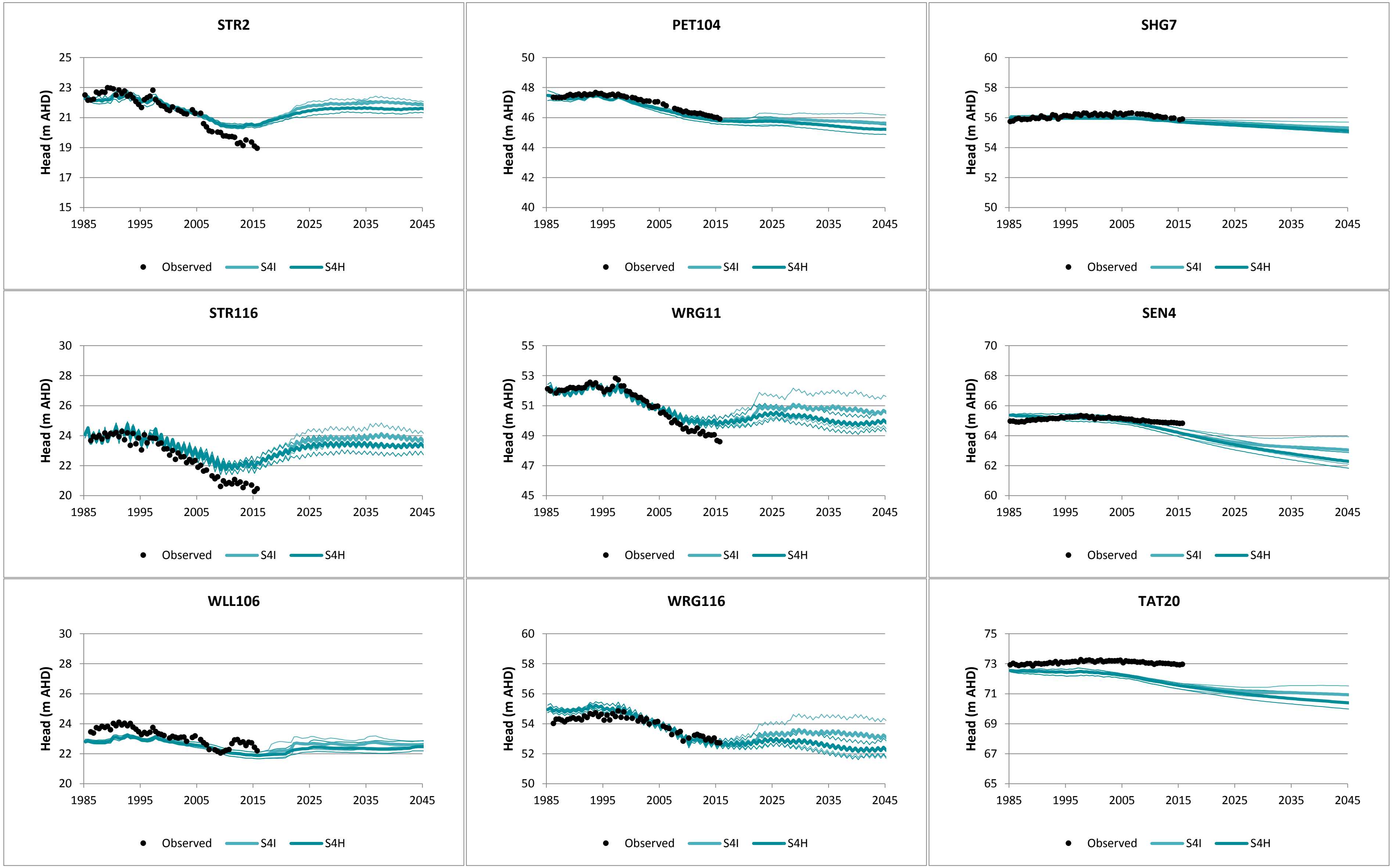

Figure 6.15. Selected hydrographs from S4 (Lower extraction) including both intermediate carbon emission scenario projections

6.2.6 Summary of mass balance projections

Diffuse recharge decreases on average over the next 30 years while point recharge is more variable and dependent on large rainfall events. Average diffuse recharge ranges from 62–85 GL/y for the high emissions which is greater than the 2006–15 average of 48–56 GL/y. Average recharge in the intermediate scenario ranges from 78–112 GL/y which is more like the average recharge from 1996–2005 (81–112 GL/y). As groundwater extraction decreases from scenario to scenario, both the groundwater outflow and groundwater evapotranspiration are progressively larger. The average storage losses continue in each scenario but are smaller in magnitude between scenarios when extraction is lower.

Groundwater extraction remains close to constant over time for all scenarios with the exception of S1I and S1H. In these full allocation scenarios, large reductions in groundwater storage causes large parts of model layer 1 to become dewatered which forces the model to lower extraction from wells in those areas (i.e. after starting at 131 GL/y, S1H 10-year averages reduce from 128–121 GL/y). The affected areas are in the south-western part of the Tatiara PWA on the coastal plain where the unconfined aquifer is relatively thin. Dry cells are not widespread or present in the other scenarios with lower extraction rates. The extraction rates in S2 vary depending on the climate data used, with 10-year averages ranging from 87–97 GL/y in S2I and 86–93 GL/y in S2H. The fact that the intermediate emissions climate dataset contains a greater number of low spring/summer rainfall years (resulting in higher extraction) than the high emissions climate projection may seem non-intuitive. However this is a simply a result of the different temporal patterns of projected rainfall in the two GCMs selected and is supported by the average changes of the six better performing GCMs for 2030 and 2050 between RCP4.5 and RCP8.5 shown in Table 6.1 (after Charles and Fu, 2014).

Average inflow fluxes show only small increases into the future suggesting that the larger fluctuations of other mass balance components within the Tatiara PWA do not cause large or immediate responses from the eastern part of the groundwater system (i.e. SA–Victoria Border) within the model projection period (ending in 2045). Potential impacts beyond this time period are likely to be seen later given the continued losses from storage and small decline in recharge fluxes projected over the next 30 years. Outflow decreases over time for only S1I and S1H while the scenarios with lower extraction rates show relatively constant or increasing outflow fluxes. This suggests that the coastal plain groundwater system becomes somewhat stable for S2, S3 and S4 while the overall continued loss of storage must be occurring elsewhere (i.e. some distance from the eastern and western boundaries). This and other results are discussed in more detail in the following chapter and are more clearly supported by projected hydrographs.

6.4 Implications for groundwater management

6.4.1 Coastal plain

The two possible resource condition limits for the coastal plain identified by Cranswick and Barnett (2017) are aquifer performance and hydraulic gradient. Aquifer performance is assessed based on the availability of groundwater within higher yielding parts of the aquifer, namely within the Padthaway Formation. The possible aquifer performance RCL proposed is to maintain a 3 m saturated thickness within the Padthaway Formation at the end of the winter monitoring round (Cranswick and Barnett, 2017). For simplicity, using model projected water levels, the RCL is considered exceeded if less than a 3 m saturated thickness is observed at any time at specified observation wells. The hydraulic gradient RCL is assessed in order to ensure that throughflow continues across and out of the coastal plain. This mitigates the risk of increased rates of rising groundwater salinity and the reversal of groundwater flow direction, which would draw groundwater of a higher salinity from the east towards irrigation areas. The hydraulic gradient RCL is to maintain a westward hydraulic gradient of greater than 0.0001 at all times. These RCLs have been assessed for a selection of representative wells (aquifer performance RCL) and pairs of wells (hydraulic gradient RCL) in Figure 6.17 and Figure 6.18 respectively for each of the extraction scenarios. The location of these wells can be seen in Figure 6.16. Note that both the high and intermediate carbon emissions climate scenarios are presented in these figures and the approximate year of any RCL exceedances for projected groundwater levels of any scenario variation are summarised in Table 6.3.

The red line in Figure 6.17 represents the aquifer performance RCL of a 3 m saturated thickness within the Padthaway Formation. This RCL is not exceeded in any scenarios for STR110 nor S2, S3 and S4 for STR111. If the simulated groundwater levels are shifted to better match the observed data for STR111 the RCL would be exceeded at approximately 2033 in S1. The aquifer performance RCL is exceeded initially in all scenarios at WLL108 but recovers in some model projections for S2, S3 and S4. Similar to STR111, the WLL105 projected groundwater levels exceed the RCL in 2035 for some scenario variations in S1 but not for the other scenarios. It should also be noted that the simulated groundwater levels underestimate the observed declining trends in wells STR111, WLL108 and WLL105 during the historical period and so it is possible that RCLs will be exceeded sooner and more frequently than these projections suggest.

The red line in Figure 6.18 has been calculated based on the minimum groundwater level projections of the up-gradient observation well and is the level at which the hydraulic gradient RCL is exceeded. That is, if the down-gradient projected groundwater level intersects this red line, the hydraulic gradient would be less than 0.0001 and the RCL would be exceeded. This occurs in the north-western and south-western observation pairs in S1 soon after 2020 (provided the simulated water levels are shifted in PRK37 to match observed historical water levels). Similarly, if the relative change in simulated water levels are considered in LAF6, the RCL is likely to be exceeded in approximately 2038 for the mid-western observation pairs for S1. The hydraulic gradient RCL is not exceeded in S2, S3 or S4 for these observation well pairs.

6.4.2 Mallee highlands

The possible resource condition limit for the Mallee highland identified by Cranswick and Barnett (2017) is to maintain a hydraulic gradient of greater than 0.0004 between selected observation well pairs. The hydraulic gradient RCL is assessed in order to ensure that throughflow continues to occur across and out of the Mallee highlands. This supports the replenishment of groundwater resource on the coastal plain (mitigating the risk of increased rates of rising salinity on the coastal plain and to reduce the impact on any changes in recharge salinity on the Mallee highlands due to irrigation recycling and clearance of native vegetation). The hydraulic gradient RCL has been assessed for a selection of observation well pairs in Figure 6.19 for each of the extraction scenarios. The location of these wells can be seen in Figure 6.16. Note that both the high and intermediate carbon emissions climate scenarios are presented in these figures and the approximate year of any RCL exceedances for projected groundwater levels of any scenario variation are summarised in Table 6.3.

The red line in Figure 6.19 has been calculated based on the minimum groundwater level projections of the up-gradient observation well and is the level at which the hydraulic gradient RCL is exceeded. That is, if the down-gradient projected groundwater levels intersect this red line, the hydraulic gradient would be less than 0.0004 and the RCL would be exceeded. The hydraulic gradient RCL is not exceeded in S1, S2, S3 or S4 for these observation well pairs. This is largely due to the similar behaviour of groundwater levels in the selected pairs.

6.4.3 Summary of projected RCL exceedances and implications

Overall the RCLs for the coastal plain are not exceeded for S2, S3 or S4 (with the exception of aquifer performance for WLL108). This suggests that these limits are unlikely to be reached under the selected climate projections and extraction rates used for these scenarios (ranging from 63–97 GL/y). However with extraction of 131 GL/y in S1 each of the coastal plain RCLs are likely to be exceeded. These exceedances would have major negative implications for the condition of groundwater resources on the coastal plain which should be avoided.

The RCL for the Mallee highlands is not exceeded in any scenario despite the continued declines in projected groundwater levels. It is possible for greater rates of extraction to occur in the Mallee highlands without exceeding the proposed hydraulic gradient RCL – see also Appendix C in Volume 2 of this report for Mallee highlands groundwater balances and brief analysis. The impact of such declines within the Tintinara-Coonalpyn PWA should be investigated in future analysis of scenario results.

Table 6.3 Summary of projected RCL exceedance dates (approximate year)

Hydrogeological zone	**RCL**	**Location**	**Scenario**			
			S1 (131 GL/y)	*S2 (89–93 GL/y)*	*S3 (84 GL/y)*	*S4 (63 GL/y)*
Coastal plain	*Aquifer performance*	STR110	-	-	-	-
		STR111	2033*	-	-	-
		WLL108	2015	2015	2015	2015
		WLL105	2045			
	Hydraulic gradient	North-western	2022	-	-	-
		Mid-western	2038*	-	-	-
		South-western	2020*	-	-	-
Mallee highland	*Hydraulic gradient*	Northern	-	-	-	-
		Central	-	-	-	-
		Southern	-	-	-	-

* RCL exceeded if projected groundwater levels are shifted by the offset that exists between observed and simulated groundwater levels in the historical period

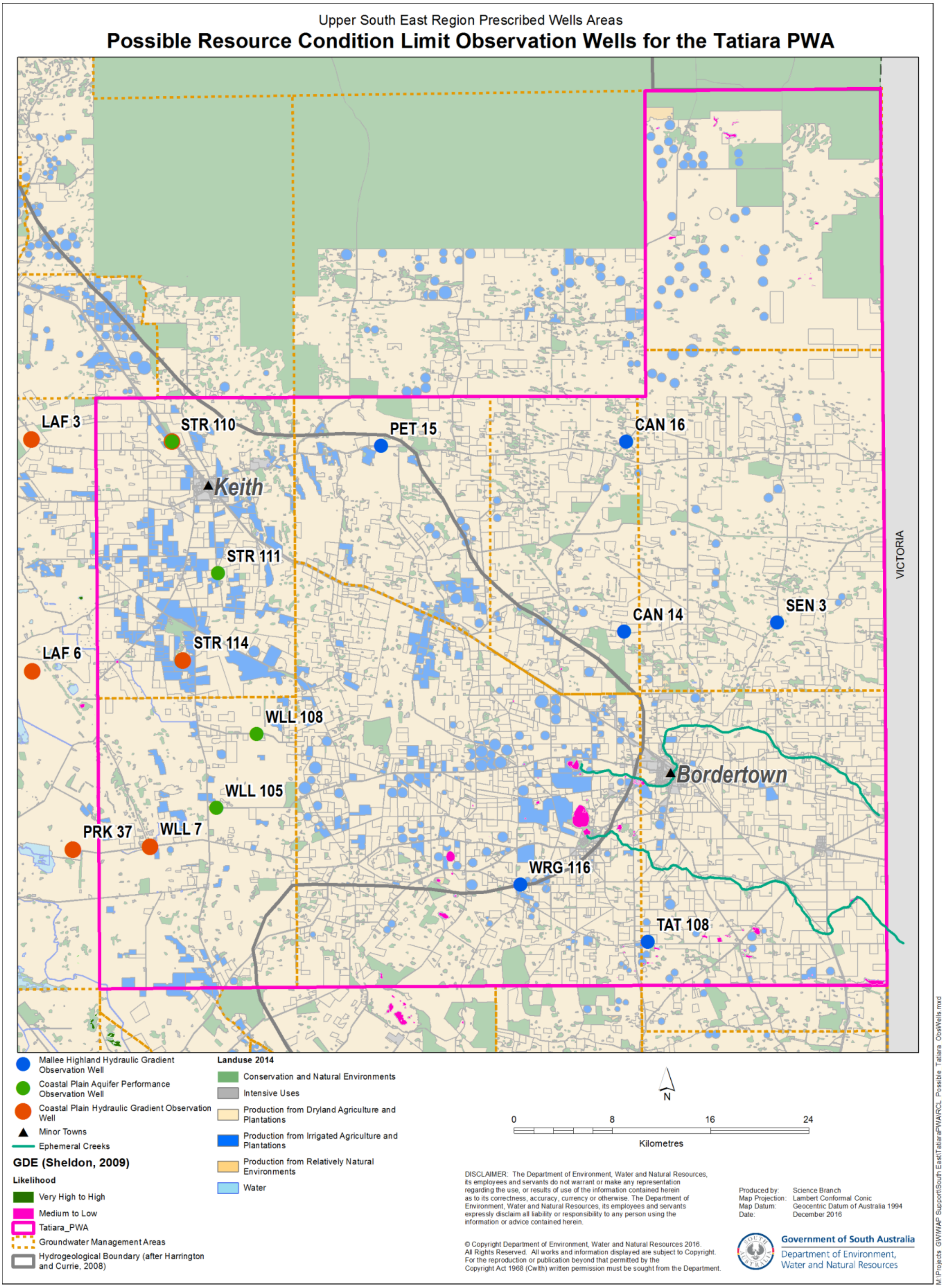

Figure 6.16. Observation wells for possible RCLs in the Tatiara PWA

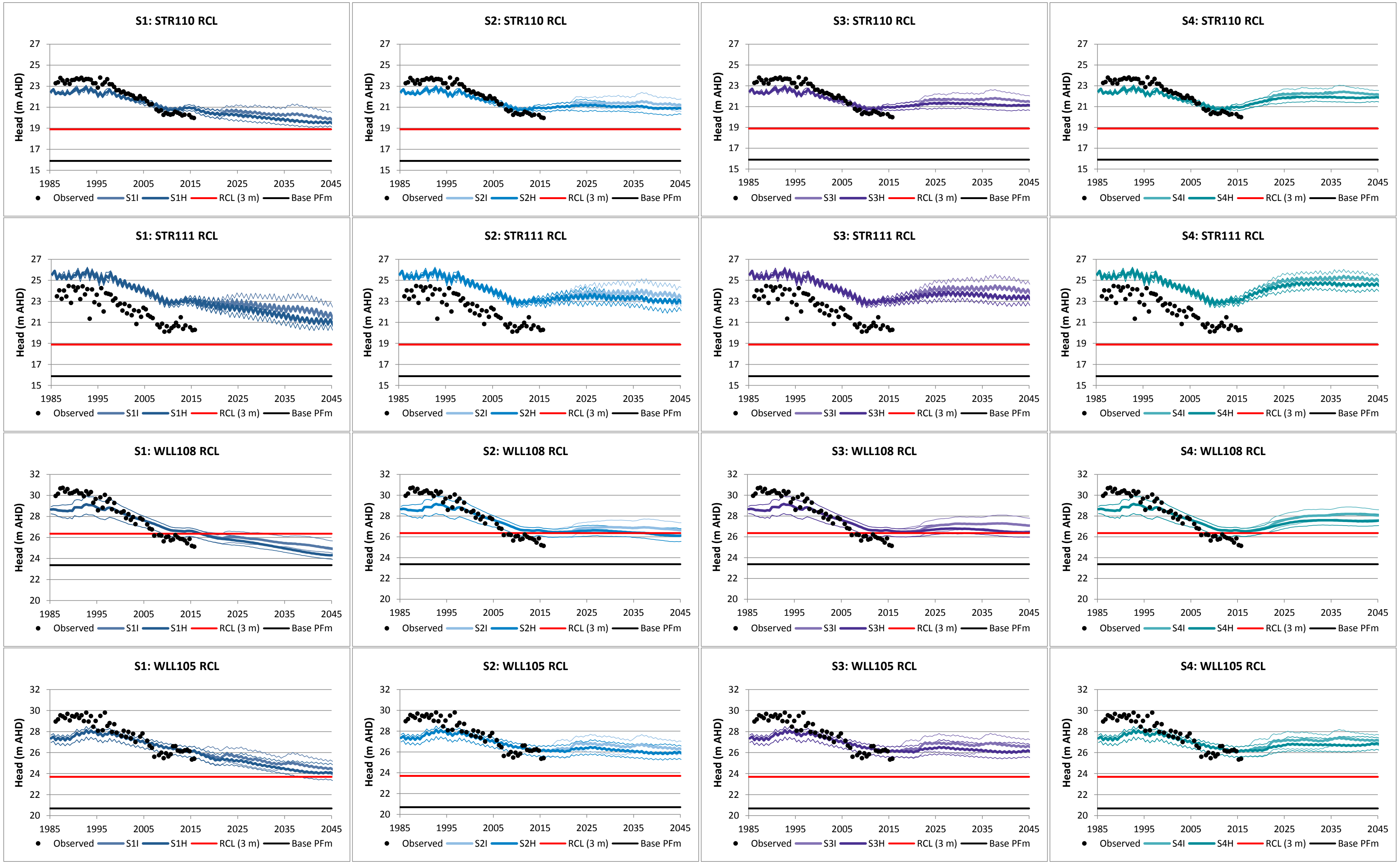

Figure 6.17. Coastal plain aquifer performance RCL (red line) for selected wells showing average (thick), minimum and maximum (thin) projected water levels

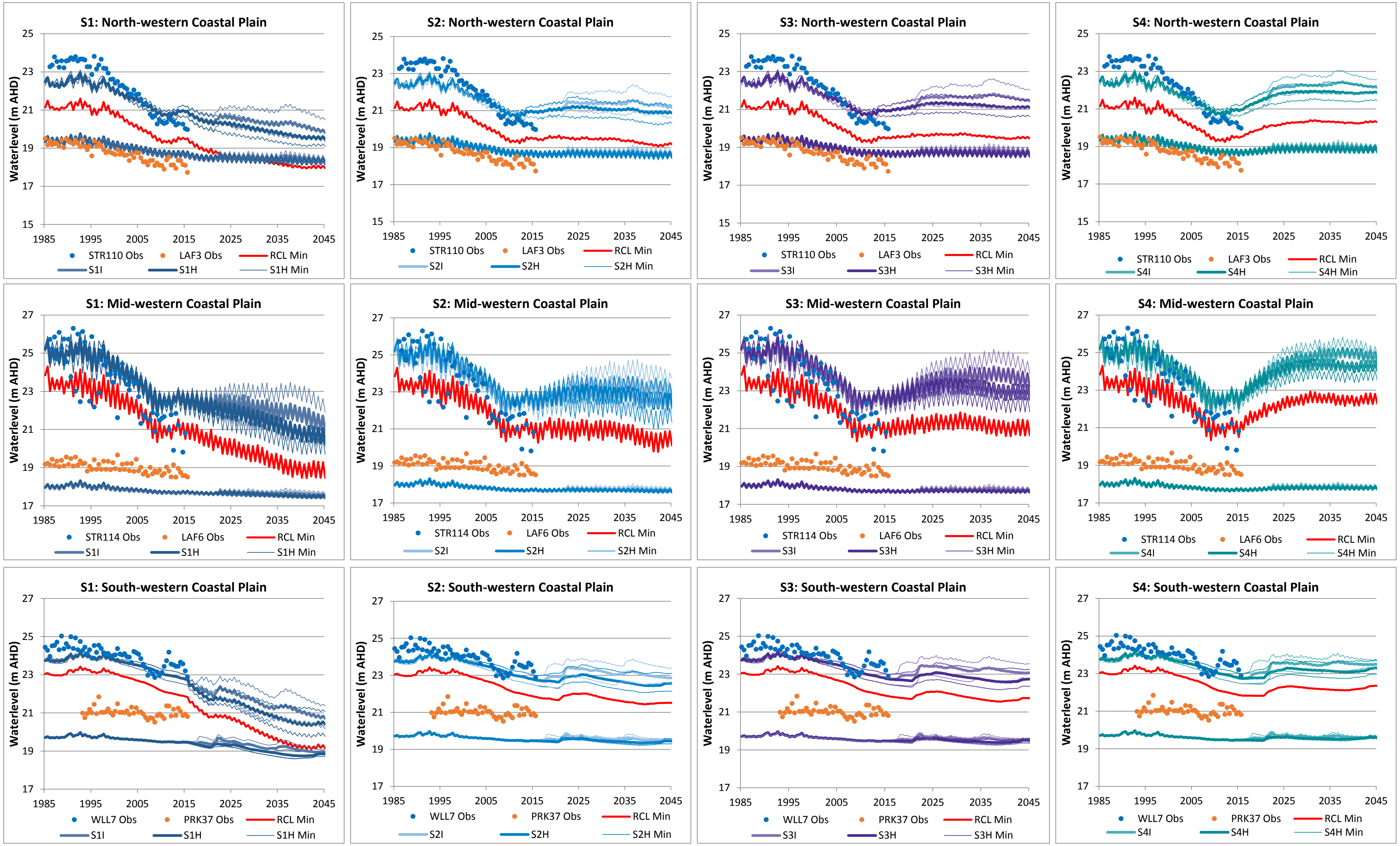

Figure 6.18. Coastal plain hydraulic gradient RCL for selected observation wells showing average (thick lines), minimum and maximum (thin lines) projected water levels and the RCL calculated based on the lowest projected water level for the high emissions scenario (represented as red line)

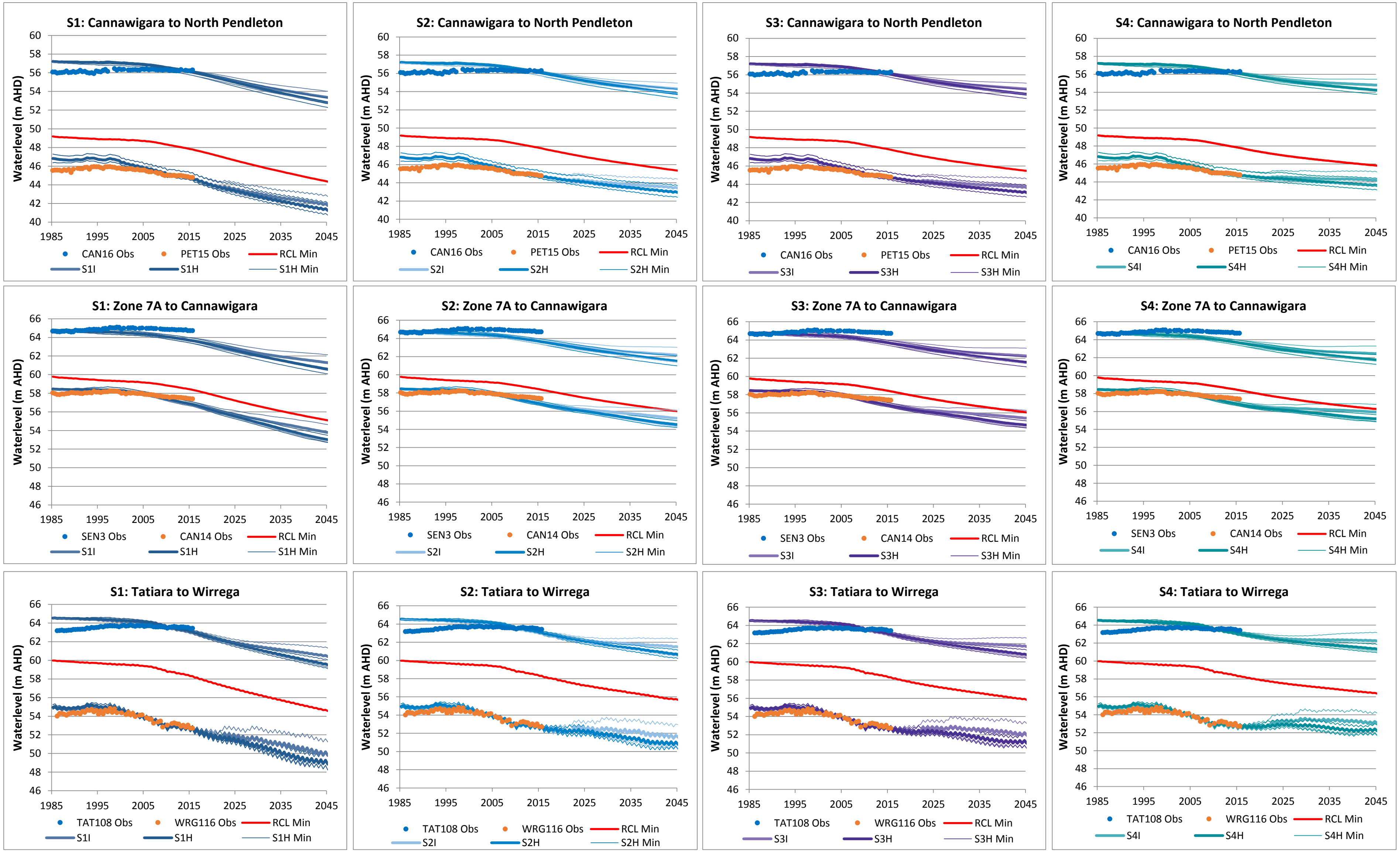

Figure 6.19. Mallee highland hydraulic gradient RCL for selected observation well pairs showing average (thick lines), minimum and maximum (thin lines) projected water levels and the RCL calculated based on the lowest projected water level for the high emissions scenario (represented as red line)

7 Model capabilities and limitations

The Tatiara PWA groundwater model has been successfully developed to simulate the regional groundwater flow patterns and changes over the last 30 years. The model simulates the responses of groundwater in the unconfined aquifers of the Mallee highlands in the east and the coastal plain in the west to changes in recharge and groundwater extraction. These are presented as changes in the groundwater balance and simulated groundwater elevations over time. Thirty-year projections under a range of future scenarios can be simulated with reference to the possible resource condition limits developed by Cranswick and Barnett (2017).

An assessment of the confidence rating for the model performance has been done for each of the 312 observation wells used in calibration. A high to medium confidence can be placed on the simulated water levels of 71% of observation wells while 15% of observation wells were simulated with a low confidence and 14% could not be assessed due to a lack of time-series data. The areas of low confidence generally simulate the groundwater level trends very well but are offset by > 2 m. These offsets are most likely caused by over or underestimates of recharge across relatively small parts of the model domain and/or uncertainty in the thickness of the unconfined aquifer in these locations. It is also likely that the spatial variability of the hydraulic parameters was not adequately represented vertically and/or horizontally in these areas where the Quaternary limestone is comprised of many discontinuous layers with different hydraulic properties. Nevertheless, it is recommended that when projected groundwater levels are used to inform resource condition limits in future scenarios, that this approach is applied using only relative simulated groundwater levels in the low confidence areas and not applied to areas where the confidence could not be assessed due to lack of time-series groundwater level observations (which mostly occurs outside of the Tatiara PWA).

The application of recharge multipliers across the entire model domain does not allow smaller areas to be adjusted and spatial variation in recharge is determined by LEACHM (i.e. unique combinations of soils, climate, landuse and irrigation type). This means that the recharge multipliers have necessarily been altered during calibration to produce the best fit overall for all observations wells. This may have introduced a calibration bias towards the areas with the most observations for which residuals are calculated (i.e. coastal plain rather than Mallee highlands) and the influence of this has not been addressed in the observation weighting scheme applied. The potential over or underestimation of recharge in particular areas has also not been explored due to the limitation of applying a single recharge multiplier. It may be possible through customised coding outside of MODFLOW and PEST to include recharge zones with different recharge multipliers for each stress period in future versions of the model.

There are a number of other sources of uncertainty in the models and their subsequent projections of groundwater levels and condition which are discussed in Chapter 5. These include parameter uncertainty and structural uncertainty associated with the groundwater model design (i.e. selection of two model layers and the assumption of no vertical interaction with underlying sediments) and of the recharge model (Morgan et al., 2017) where vertically uniform soils and only two depth profiles were represented. These should also be noted as limitations to the model results presented in this report whilst at the same time considering the vast improvements that have been made following the previous pilot study model of Wood (2011).

Groundwater flow through karst features has not been modelled explicitly but is approximated using an equivalent porous medium approach. A number of high transmissivity zones were applied in areas where karst features are known to be present but this is unlikely to accurately represent the aquifer behaviour on very small scales (i.e. < 200 m).

8 Conclusions and recommendations

Overview

The Tatiara PWA groundwater model has been developed to investigate the influence of varying groundwater extraction and climate induced stresses on groundwater resources in the future. To do this robustly, the model should simulate the regional levels and trends of the groundwater system over a historical period in response to the observed changes in rainfall and historical variations of groundwater extraction. This has been done using an iterative calibration approach using automated parameter estimation software in combination with manual adjustments based on hydrogeological knowledge. A family of three groundwater models were calibrated based on a range of different groundwater extraction scaling factors applied to historical estimates, in order to capture some of the uncertainty introduced by unmetered extraction. The outputs of the model are tailored towards informing possible resource condition limits (RCLs) developed by Cranswick and Barnett (2017) for the coastal plain and Mallee highland hydrogeological zones. Four scenarios of groundwater extraction were projected into the future and combined with two climate scenarios (each with three climate datasets). The RCLs are not exceeded on the Mallee highlands or the three lowest extraction scenarios on the coastal plain. However the full allocation scenario results in RCL exceedances for the coastal plain and larger groundwater level declines in the Mallee highlands. Full allocation is therefore not recommended on the coastal plain while there is potential for greater extraction on the Mallee highlands prior to RCLs being threatened. Additional scenarios, testing the influence of greater extraction from the Mallee highlands areas, may provide a useful alternative to the historical dominance of extraction from the coastal plain groundwater resources.

Calibrated models

Overall, the models show good agreement between the observed and simulated groundwater system in terms of groundwater level and trends. Declining trends are slightly under-predicted in parts of the coastal plain over the last five to ten years of the calibration period and over-predicted in the Mallee highland over the last ten years. This is a result of the recharge being reduced across the entirety of the model domain in order to better match the larger groundwater level declines in coastal plain. The scaled root mean squared (SRMS) error was less than 3% for all three models with root mean squared (RMS) errors of less than 1.8 m and absolute residual means of less than 1.3 m (by comparison with 9781 observations from 312 wells). Groundwater mass balances of the Tatiara PWA are considered to be improvements on previous assessments which generally fall within the variation captured by the model. The average groundwater recharge for the three calibrated models from 1986–2000 is 125 GL/y which shows large variations from year to year (e.g. 53 to 231 GL/y). The second half of the calibration period (2001–15) has lower recharge rates averaging just 61 GL/y (with a range from 37–103 GL/y). Associated with this reduction in recharge, the average reduction in storage increases from 12 to 47 GL/y between the two averaging periods. Outflow and groundwater ET are also reduced on average between the first and second halves of the calibration period by 16 and 8 GL/y respectively. Groundwater extraction and groundwater inflow from the east remain relatively constant but vary slightly for each of the three calibrated models.

An assessment of the confidence rating for the model performance has been done for each of the 312 observation wells used in calibration. A high to medium confidence can be placed on the simulated water levels of 71% of observation wells while 15% of observation wells were simulated with a low confidence and 14% could not be assessed due to a lack of time-series data. The areas of low confidence generally simulate the groundwater level trends well but are offset by > 2 m. These offsets are most likely caused by both overestimates and underestimates of recharge across relatively small parts of the model domain and/or uncertainty in the thickness of the unconfined aquifer in these locations. It is also likely that the spatial variability of the hydraulic parameters was not adequately represented vertically and/or horizontally in these areas where the Quaternary limestone is comprised of many discontinuous layers with different hydraulic properties. Nevertheless, it is recommended that when projected groundwater levels are used to inform resource condition limits in future scenarios, that this approach is applied using only relative simulated groundwater levels in the low confidence areas and not applied to areas where the confidence could not be assessed due to lack of time-series groundwater level observations.

Projected scenarios

The three calibrated groundwater models are used in combination to investigate the impacts of potential future groundwater extraction and climate change within the Tatiara PWA. Four extraction scenarios have been developed:

- **S1 Full allocation extraction** (138.1 GL) – 2016/17 allocation data after removal of carry-over totals
- **S2 Periodic extraction** (101.9, 81.5, 61.1 GL) – current extraction as a base rate that is increased by 25% or decreased by 25% if spring-summer rainfall is below or above the 25th and 75th percentiles respectively at the Keith weather station (25507)
- **S3 Current extraction** (81.5 GL) – average of 2013/4, 2014/5 and 2015/6 metered data
- **S4 Lower extraction** (61.1 GL) – current use reduced by 25%

These extraction scenarios are combined with two selected climate change projections for high and intermediate carbon emissions (denoted for example as S2H and S2I with each having three climate data variations) based on the SA Climate Ready datasets developed by the Goyder Institute. These climate datasets are applied to the Upper South East recharge model (Morgan et al., 2017) to produce estimates of projected diffuse recharge that are then applied to the groundwater model. The scenarios are described below with reference to the Tatiara PWA extraction rates.

The average diffuse recharge decreases over the next 30 years from 94 GL/y down to 89 GL/y in the intermediate emissions scenario and from 73 GL/y down to 68 GL/y in the high emissions scenario. The range of average diffuse recharge is 62–85 GL/y for the high emissions scenario which is greater than the 2006–15 average of 48–56 GL/y. The range of average recharge in the intermediate emissions scenario is 78–112 GL/y which is more like the average recharge from 1996–2005 (81–112 GL/y). Point recharge is more variable and dependent on large rainfall events ranging on average from 4–10 GL/y and 1–6 GL/y for the intermediate and high emissions scenarios respectively. As groundwater extraction decreases from scenario to scenario, both the groundwater outflow and groundwater evapotranspiration are progressively larger. The average storage losses continue in each scenario but are smaller in magnitude as extraction is reduced between scenarios. Average inflow fluxes show only small increases into the future suggesting that the larger fluctuations of other mass balance components within the Tatiara PWA do not cause large or immediate responses from the eastern part of the groundwater system (i.e. SA–Victoria Border) within the model projection period (ending in 2045). Potential impacts beyond this time period are likely to be seen later given the continued losses from storage and the gradual decline in average recharge projected over the next 30 years. Outflow decreases over time for only S1I and S1H while the scenarios with lower extraction rates show relatively constant or increasing outflow fluxes. This suggests that the coastal plain groundwater system becomes somewhat stable for S2, S3 and S4 while the overall continued loss of storage occurs in the Mallee highland adjacent to the coastal plain due to historical groundwater level declines.

Implications for groundwater management

Overall the RCLs for the coastal plain are not exceeded for S2, S3 or S4 (with the exception of aquifer performance for WLL108). This suggests that these limits are unlikely to be reached under the selected climate projections and extraction rates used for these scenarios (ranging from 63–97 GL/y). However with extraction of 131 GL/y in S1, each of the coastal plain RCLs are likely to be exceeded in the near future. These exceedances would have major negative implications for the condition of groundwater resources on the coastal plain which should be avoided. The RCL for the Mallee highlands is not exceeded in any scenario despite the continued declines in projected groundwater levels. It is possible for greater rates of extraction to occur in the Mallee highlands without exceeding the possible hydraulic gradient RCL.

Recommendations

Recommendations can be separated into two groups; those relating to the further development of RCLs and subsequent implications for groundwater management decisions, and those related to additional future scenarios and the predictive uncertainty of the Tatiara PWA groundwater model.

The possible RCLs (after Cranswick and Barnett, 2017) have not yet been extensively tested through engagement with stakeholders and the pathway towards final RCLs is not entirely clear from a technical perspective. This pathway could be more confidently identified through the following improvements:

1) The detailed characterisation of the Padthaway Formation base elevation surface on the coastal plain – currently poorly defined by limited hydrostratigraphic datasets
2) The detailed characterisation of the spatial extent of Padthaway Formation where the saturated thickness is greater than 3 m (i.e. current proposed RCL) – it is unlikely that the Padthaway Formation would be found across entire coastal plain and the RCL is therefore not applicable across the entirety of the coastal plain, a more generic RCL may be required in future
3) Determination of an acceptable rate of decline for groundwater levels in the Mallee highlands or maximum drawdown surface – currently not identified as a RCL or linked to the hydraulic gradient RCL
4) Developing visual representations (i.e. spatial rather than single hydrographs) of projected groundwater levels relative to RCLs, once RCLs have been finalised – currently limited due to issues noted in recommendations 1–3.

The base scenarios presented in this report represent a range of possible extraction and climate futures with changes in extraction applied to the whole model domain. The largest changes to the groundwater balance occur on the coastal plain and have an ongoing influence on changes observed in the Mallee highlands. Scenarios where these two hydrogeological zones are managed independently have not been explored and neither have possible groundwater trade scenarios. It is possible that a shift in the distribution of extraction towards the east would enable greater volumes of groundwater to be extracted without exceeding RCLs. Additional scenarios to investigate this could include scenarios similar to, for example:

5) Current extraction on the coastal plain with an additional 50 GL extracted from the Mallee highlands;
6) Lower extraction on the coastal plain with additional 80 GL extracted from the Mallee highlands;

The predictive uncertainty of the models has been somewhat constrained by the use of three independent calibrations through the iterative use of PEST and manual alterations. Yet the parameter and structural uncertainties discussed in Chapter 5 still persist, as do the limitations of the current family of models discussed in Chapters 4 and 7. To better constrain the predictive uncertainty of model results, it is recommended that future refinement of the models should include at least the following:

7) Incorporate greater flexibility in the way recharge multipliers are applied to the groundwater model using spatial zones in addition to time varying multipliers
8) Apply more than two profile depths (e.g. 5, 10, 15, 20, 40 m) for recharge model estimates to more accurately capture the seasonality and lag between rainfall and subsequent recharge
9) Develop greater confidence in the bottom elevation surface of the MGL aquifer as it thins towards the west beneath the coastal plain
10) Consider the use of pilot points for aquifer hydraulic properties which could be guided by aquifer test values and in a relative sense, by the spatial variability of abundant airlift yield data.

9 Units of measurement

9.1 Units of measurement commonly used (SI and non-SI Australian legal)

Name of unit	Symbol	Definition in terms of other metric units	Quantity
day	d	24 h	time interval
gigalitre	GL	10^6 m^3	Volume
gram	g	10^{-3} kg	Mass
hectare	ha	10^4 m^2	Area
hour	h	60 min	time interval
kilogram	kg	base unit	mass
kilolitre	kL	1 m^3	volume
kilometre	km	10^3 m	length
litre	L	10^{-3} m^3	volume
megalitre	ML	10^3 m^3	volume
metre	m	base unit	length
microgram	µg	10^{-6} g	mass
microliter	µL	10^{-9} m^3	volume
milligram	mg	10^{-3} g	mass
millilitre	mL	10^{-6} m^3	volume
millimetre	mm	10^{-3} m	length
minute	min	60 s	time interval
second	s	base unit	time interval
tonne	t	1000 kg	mass
year	y	365 or 366 days	time interval

10 Glossary

Act (the) — In this document, refers to the *Natural Resources Management (SA) Act 2004,* which supersedes the *Water Resources (SA) Act 1997*

Adaptive management — A management approach often used in natural resource management where there is little information and/or a lot of complexity, and there is a need to implement some management changes sooner rather than later. The approach is to use the best available information for the first actions, implement the changes, monitor the outcomes, investigate the assumptions, and regularly evaluate and review the actions required. Consideration must be given to the temporal and spatial scale of monitoring and the evaluation processes appropriate to the ecosystem being managed.

Aquifer — An underground layer of rock or sediment that both stores and transmits water

Aquifer, confined — An aquifer that is overlain in part or wholly by an aquitard (see also 'confining layer') and the water is held at greater than atmospheric pressure; water in a penetrating well will rise above the surface of the aquifer unless seriously impacted by groundwater extraction

Aquifer, unconfined — Aquifer in which the upper surface has free connection to the ground surface and the water surface is at atmospheric pressure

Aquitard — A layer in the geological profile that separates two aquifers and restricts the flow between them

Carry-over — A licensed volume of water equivalent to the unused volume of allocation at the end of the preceding water use year, or 20% of the licensee's annual allocation for the preceding year, whichever is lesser

Climate futures analysis — a method for the grouping of multiple 'GCM' climate projections according to the amount of change they project in two or more climate variables (e.g. average projected future change in temperature and rainfall compared to a baseline period). This may be undertaken to determine where there is the most agreement between models in relation to the likely future change in primary climate variables

Climate projection — a scenario of future climate, generally resulting from running a GCM with a specified greenhouse gas concentration scenario (or RCP). A projection differs from a prediction in that it is conditional on the representation of a particular model (GCM) and the uncertain assumptions of the model inputs (primarily the greenhouse gas concentration scenario, or RCP)

Climate scenario — description of the possible future climate according to a particular GCM and influenced by a specific RCP

Cone of depression — An inverted cone-shaped space within an aquifer caused by a rate of groundwater extraction that exceeds the rate of recharge; continuing extraction of water can extend the area and may affect the viability of adjacent wells, due to declining water levels or water quality

Confining layer — A geological unit which has low permeability that restricts the flow of water and forms the upper bound of a confined aquifer; a body of impermeable material adjacent to an aquifer; see also 'aquifer, confined'

DEWNR — Department of Environment, Water and Natural Resources (Government of South Australia)

Discretisation — the characterisation of smaller units of distance (i.e. meters) and time (i.e. days) that are combined using equations within a mathematical model, they can be defined using regularly or irregularly spaced intervals.

Downscaling – The process of deriving local climate change impacts from large scale global climate models

Ecosystem — Any system in which there is an interdependence upon, and interaction between, living organisms and their immediate physical, chemical and biological environment

Ephemeral streams or wetlands — Those streams or wetlands that usually contain water only on an occasional basis after rainfall events or due to groundwater discharge. Many arid zone streams and wetlands are ephemeral.

Evapotranspiration — The total loss of water as a result of transpiration from plants and evaporation from land, and surface water bodies

GCM — global climate model, sometimes also referred to as generalised circulation model. These are mathematical models that integrate systems of differential equations describing the dynamic processes and interaction between the atmosphere, land and ocean. GCMs typically have a grid resolution on the order of 150 x 250 km and require downscaling for local-scale applications; see also 'statistical downscaling'

GDE — Groundwater dependent ecosystem

GMA — Groundwater Management Area

Groundwater — Water occurring naturally below ground level or water pumped, diverted and released into a well for storage underground; see also 'underground water'

Hydraulic conductivity (K) — A measure of the ease of flow through aquifer material: high K indicates low resistance, or potential high flow conditions; measured in metres per day

Hydrogeology — The study of groundwater, which includes its occurrence, recharge and discharge processes, and the properties of aquifers; see also 'hydrology'

Impact — A change in the chemical, physical, or biological quality or condition of a water body caused by external sources

IPCC – Intergovernmental Panel on Climate Change

Irrigation — Watering land by any means for the purpose of growing plants

Irrigation season — The period in which major irrigation diversions or extractions occur, usually starting in October–November and ending in April–May but is defined as October to March in this report

Licence — A licence to take water in accordance with the Act; see also 'water licence'

Licensee — A person who holds a water licence

m AHD — Defines elevation in metres (m) according to the Australian Height Datum (AHD)

Model — A conceptual or mathematical means of understanding elements of the real world that allows for predictions of outcomes given certain conditions. Examples include estimating storm run-off, assessing the impacts of dams, groundwater flow or predicting ecological response to environmental change

MODFLOW — A three-dimensional, finite difference code developed by the USGS to simulate groundwater flow

Monitoring — (1) The repeated measurement of parameters to assess the current status and changes over time of the parameters measured (2) Periodic or continuous surveillance or testing to determine the level of compliance with statutory requirements and/or pollutant levels in various media or in humans, animals, and other living things

Natural recharge — The infiltration of water into an aquifer from the surface (rainfall, streamflow, irrigation etc). See also recharge area, artificial recharge

Observation well — A narrow well or piezometer whose sole function is to permit water level measurements

Permeability — A measure of the ease with which water flows through an aquifer or aquitard, measured in m^2/d

Potentiometric head — The potentiometric head or surface is the level to which water rises in a well due to water pressure in the aquifer, measured in metres (m); also known as piezometric surface

Prescribed water resource — A water resource declared by the Governor to be prescribed under the Act, and includes underground water to which access is obtained by prescribed wells. Prescription of a water resource requires that future management of the resource be regulated via a licensing system.

Prescribed well — A well declared to be a prescribed well under the Act

PWA — Prescribed Wells Area

RCP — representative concentration pathway, a scenario of possible future global atmospheric greenhouse gas and aerosol concentrations, applied in GCMs when projecting future climate change.

Recharge area — The area of land from which water from the surface (rainfall, streamflow, irrigation, etc.) infiltrates into an aquifer. See also artificial recharge, natural recharge

Recommended extraction limit (REL) — The volume of extraction for consumptive use that can be sustained over time while keeping the groundwater system from exceeding relevant resource condition limits

Resource condition indicator (RCI) — with respect to groundwater resources, a parameter that can be directly monitored such as groundwater levels or groundwater salinity which gives an indication of the state of the resource; can be derived from other field observations such as the groundwater discharge (baseflow) component of river flow or estimates of aquifer storage.

Resource condition limit (RCL) — with respect to groundwater resources, a selected resource condition indicator beyond which there is an unacceptable risk to the economic, social and environmental values associated with the resource

Resource condition trigger (RCT) — with respect to groundwater resources, a specified level or metric of a resource condition indicator that is breached warning that there is an increased risk to a resource condition limit being reached. The trigger is intended to initiate a management response which may be further investigation or more swift action related to licensed allocations.

SA Geodata — A collection of linked databases storing geological and hydrogeological data, which the public can access through the offices of PIRSA. Custodianship of data related to minerals and petroleum, and groundwater, is vested in PIRSA and DWLBC, respectively. DWLBC should be contacted for database extracts related to groundwater

Salinity — The concentration of dissolved salts in water or soil, expressed in terms of concentration (mg/L) or electrical conductivity (EC)

Spatial variability — Where the value of a parameter is changes across some distance or area

Specific storage (S_s) — The amount of stored water realised from a unit volume of aquifer per unit decline in head; measured in m^{-1}

Specific yield (S_y) — The volume ratio of water that drains by gravity, to that of total volume of the porous medium. It is dimensionless

Statistical downscaling — a process of inferring high-resolution information from low-resolution information (e.g. developing local-scale weather information from regional-scale generalised circulation model outputs that are statistically consistent with historical observed data)

TDS — Total dissolved solids, measured in milligrams per litre (mg/L); a measure of water salinity

Temporal variability — When the value of a parameter changes in time

Threshold level — See 'Resource condition threshold level'

Timelag — broadly refers to the an interval of time between two related phenomena (such as cause and its effect); more specifically for the Upper South East it may refer to the period of time between rainfall and subsequent recharge

Transmissivity (T) — A measure of the ease of flow through aquifer material: high T indicates low resistance, or potential high flow conditions; measured in metres squared per day and can calculated by multiplying the hydraulic conductivity by the saturated thickness of the aquifer or by conducting aquifer tests

Underground water (groundwater) — Water occurring naturally below ground level or water pumped, diverted or released into a well for storage underground

Water allocation — (1) In respect of a water licence means the quantity of water that the licensee is entitled to take and use pursuant to the licence. (2) In respect of water taken pursuant to an authorisation under s.11 means the maximum quantity of water that can be taken and used pursuant to the authorisation

WAP — Water Allocation Plan; a plan prepared by a water resources planning committee and adopted by the Minister in accordance with the Act

Water body — Includes watercourses, riparian zones, floodplains, wetlands, estuaries, lakes and groundwater aquifers

Watercourse — A river, creek or other natural watercourse (whether modified or not) and includes: a dam or reservoir that collects water flowing in a watercourse; a lake through which water flows; a channel (but not a channel declared by regulation to be excluded from the this definition) into which the water of a watercourse has been diverted; and part of a watercourse

Water quality data — Chemical, biological, and physical measurements or observations of the characteristics of surface and groundwaters, atmospheric deposition, potable water, treated effluents, and wastewater, and of the immediate environment in which the water exists

Water quality monitoring — An integrated activity for evaluating the physical, chemical, and biological character of water in relation to human health, ecological conditions, and designated water uses

Well — A well (also known as a 'bore', or 'borehole') is usually a drilled hole constructed by a licensed driller for the purposes of obtaining or monitoring groundwater, but may also include an artificial excavation used for the purpose of collecting, storing or taking groundwater.

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